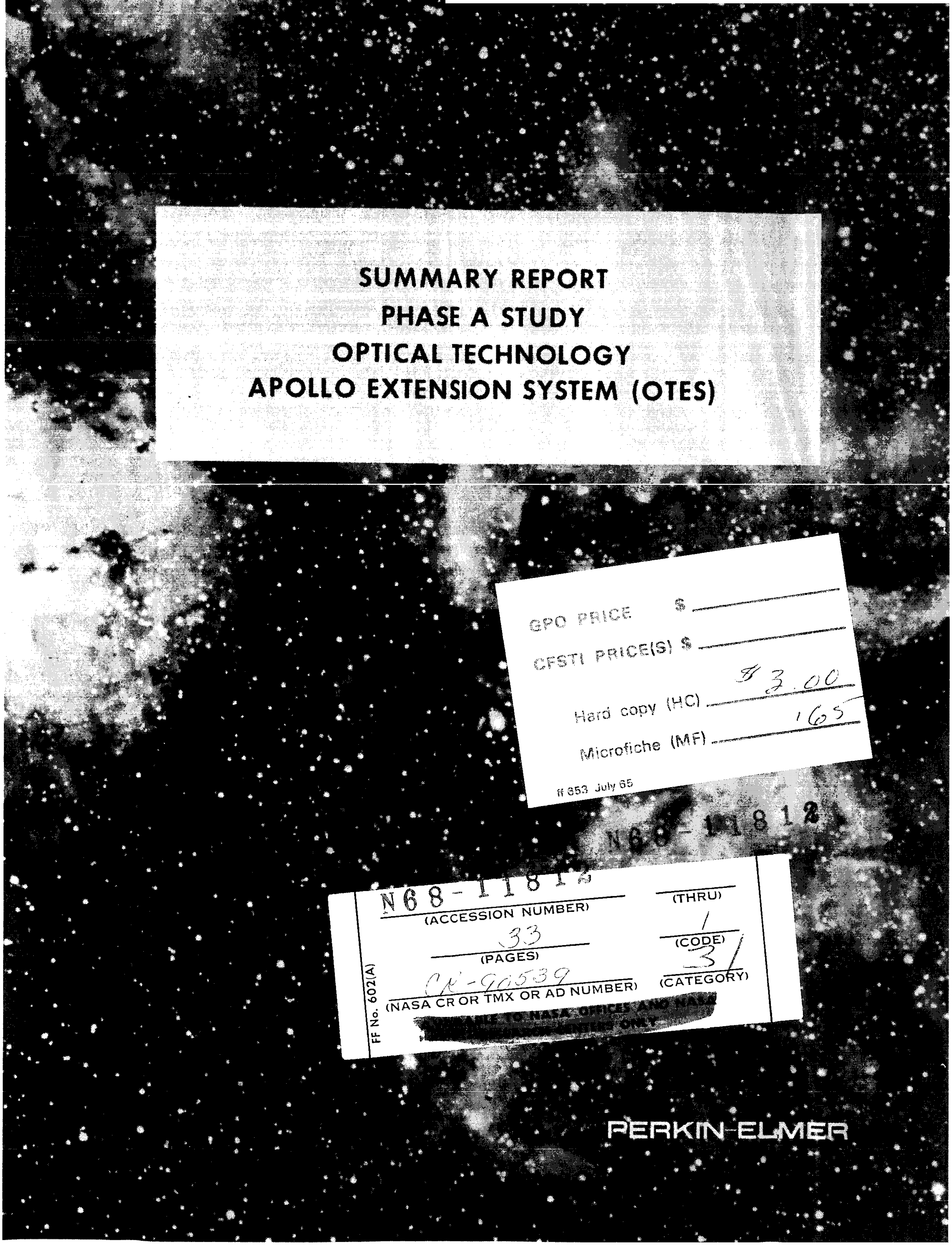


SUMMARY REPORT
PHASE A STUDY
OPTICAL TECHNOLOGY
APOLLO EXTENSION SYSTEM (OTES)

PERKIN-ELMER

Lecturer: "...Fundamentally, a star is a
pretty simple structure..."

Voice from the Audience: "You would look
pretty simple, too, at a distance
of ten parsecs."

Colloquium in Cambridge University,
1954

LMSC-A848299 ● 15 SEPTEMBER 1967

LMSC-A848299

OPTICAL TECHNOLOGY EXPERIMENT SYSTEM (OTES)

PHASE II – CONDENSED SUMMARY REPORT

LMSC Input

Submitted to
The Perkin-Elmer Corporation

In Support of Prime Contract NASA 8-20255
With NASA/Marshall Space Flight Center (MSFC)
Huntsville, Alabama

Covering Effort Performed Under Subcontract No. 15653-I and IA

Approved Dale L Hannaford
D. L. Hannaford
OTES Program Manager

Lockheed

MISSILES & SPACE COMPANY

A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION

SUNNYVALE, CALIFORNIA

PERKIN-ELMER

OPTICAL GROUP NORWALK, CONNECTICUT

LOCKHEED

ENGINEERING REPORT NO. 8900

Optical Technology Apollo
Extension System (OTES)
Phase A Study (Summary Report)

DATE: October 1967

PREPARED FOR: Astrionics Laboratory
Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama

Contract NAS 8-20255
SPO 27557

H. F. Wischnia

Herbert F. Wischnia, Program Leader

Approved: H. S. Hemstreet

Harold S. Hemstreet, Director
Advanced Systems

FOREWORD

This Condensed Summary Report briefly describes the effort accomplished by Lockheed Missiles & Space Company in support of the Perkin-Elmer Corporation activities on the Optical Technology Apollo Extension System (OTAES) study program. Results of the Phase II study are summarized here. Material covering the optical payload and experiment studies is being prepared by the Perkin-Elmer Corporation for integration with the enclosed report and submittal to NASA/MSFC under prime contract NASA 8-20255. A more detailed description of the LMSC effort is contained in the Phase II Final Technical Report (LMSC-A848294, dated 1 August 1967).

LIST OF ACRONYMS

AAP	Apollo Applications Program
AM	Airlock Module
ATM	Apollo Telescope Mount
CG	Center of Gravity
CMG	Control Moment Gyro
CSM	Command and Service Module
EVA	Extravehicular Activity
IU	Instrument Unit
KSC	Kennedy Space Center
LM	Lunar Module
LM-A	Lunar Module — Ascent Stage
LMSC	Lockheed Missiles & Space Company
LOS	Line of Sight
MDA	Multiple Docking Adapter
MSC	Manned Spacecraft Center
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
OMRF	Orbital Mirror Recoating Facility
OSR	Optical Surface Reflectance
OTAES	Optical Technology Apollo Extension System
OTES	Optical Technology Experiment System
OWS	Orbital Workshop
P-E	Perkin-Elmer Corporation
SETA	Systems Effectiveness Tradeoff Analysis
SLA	Spacecraft — LM Adapter
T/V	Thermal/Vacuum

INTRODUCTION

Phase II of the conceptual design analysis of a manned Optical Technology Experiment System (OTES) was initiated on 16 November 1966. Perkin-Elmer Corporation (P-E), a prime contractor to Marshall Space Flight Center (MSFC), held primary responsibility for optical system and experiment conceptual design. LMSC, working closely with P-E as spacecraft and system integrating subcontractor, performed analyses in the following areas:

- Spacecraft Concept Design
- Preferred Concept System Integration
- Attitude Control System Analysis
- Thermal Control System Analysis
- Crew Participation Analysis
- Reliability/Safety Analysis
- Program Planning and Support (Resources Planning) Analyses

Primary objective of the Phase II study was to generate a conceptual design for a manned OTES using a 2-m, seven-segment, active-optics primary mirror telescope system mated to the Apollo Telescope Mount (ATM) rack. The Lunar Module (LM-A) would be used as the control center and life cell for the OTES spacecraft. The primary mode of OTES operation is the clustered mode in which the OTES is docked to an AAP cluster. The AAP cluster is a space station formed by docking four separately launched vehicles via a central multiple docking adapter. The OTES spacecraft would also be capable of operating in the undocked, or independent, mode.

Several design approaches were studied for the OTES spar configuration. The best features of a number of the candidate approaches were combined to form the conceptual approach to the OTES. The selected system, in addition to satisfying primary OTES mission objectives, shows substantial promise for technology developments and subsequent growth to a larger telescope system for future mission applications in stellar observation and photography.

SYSTEM CONSIDERATIONS

Overall general program objectives for OTES are as follows:

- Demonstrate successful advancement of optical technology prior to commitment to a full-scale 3-m (or larger) OTES system
- Launch in 1973
- Provide a long-life, reliable space system
- Assure maximum economy by using fully qualified "off-the-shelf" AAP hardware and techniques

The OTES mission cluster, for purposes of analysis, has been identified as the Cluster X AAP flight configuration for earth orbit missions. Postulated mission parameters for OTES are shown in Fig. 1. Reliability requirements call for a minimum 2-yr mission with a system goal of 0.90 and a 0.999 probability of crew survival. Crew tasks, based totally on AAP cluster mission planning, would include direct or remote operation of experiments, equipment maintenance, mirror segment removal and replacement, mirror segment recoating in space, and film retrieval. The desired primary mirror operating temperature, to be controlled by passive thermal control techniques, is -80° C. Thermal gradients across the primary mirror must be less than 1° C. The attitude-control system flexure pivot defined for AAP is characterized by the following parameters:

- Pitch and yaw: ±3 deg with caging within 10 sec
- Roll: ±95 deg with maximum roll error of 10 arc min
- No power for caging mode
- Ground loads (vertical and lateral): per pivot limit = 2,500 lb, ultimate = 4,000 lb; per pivot-pair limit = 5,000 lb, ultimate = 8,000 lb
- Launch loads with spar caged: 5 g vertical; 5 g lateral

ORBIT	250 NAUTICAL MILE, CIRCULAR, INCLINED 28.3 DEG.
PAYLOAD	29,135 LB (SATURN 1B CAPABILITY TO 240 NM ORBIT = 29,800)
LIFE •	2-YEAR MINIMUM; 10 YEARS WITH RESUPPLY/MAINTENANCE; 0.90 PROBABILITY OF SUCCESS; 0.999 PROBABILITY OF CREW SURVIVAL
GROUND STATION	LAUNCH: KSC OPTICAL: NEW OTES STATION (LOCATION TO BE DECIDED) MANNED: HOUSTON - MSC
REQUIREMENTS	THERMAL GRADIENT: ±0.5 °F ATTITUDE CONTROL: ±2.5 ARC SECONDS
OPERATION MODES	AAP CLUSTER — INDEPENDENT

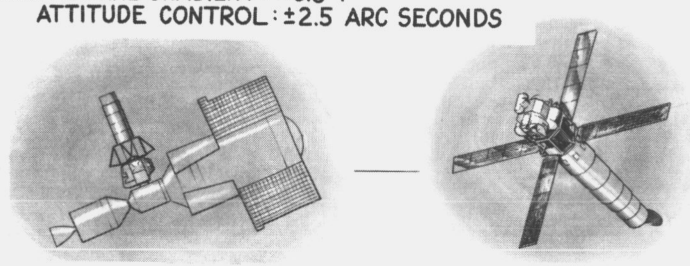


Fig. 1 OTES Postulated Mission Parameters

TWO ADDITIONAL IU SPACERS

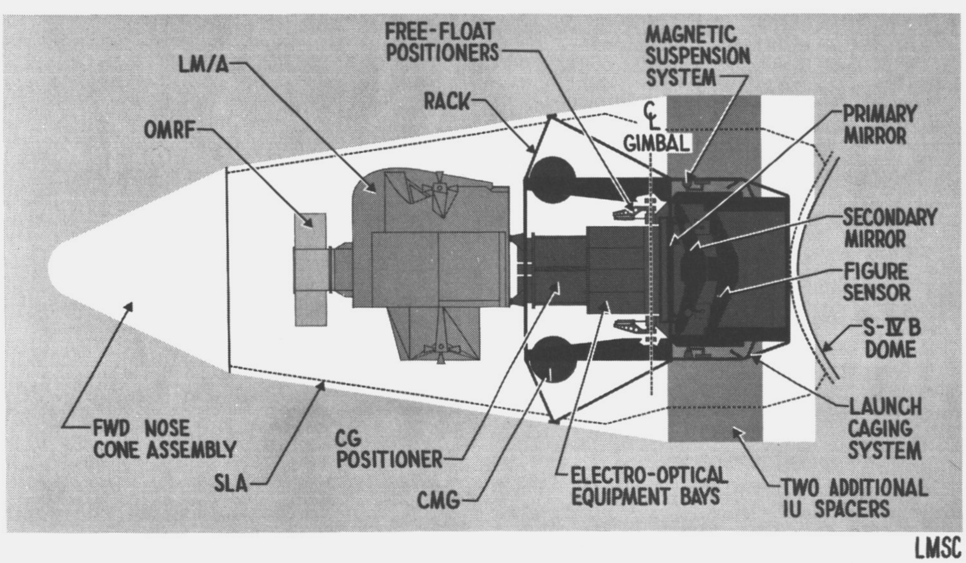


Fig. 2 Launch Configuration

The attitude-control and pointing subsystem must maintain accuracies to ±2.5 arc sec. The OTES launch will be accomplished by a Saturn IB booster. With launch to a 240-nm orbit inclined 28.3 deg toward the north, the gross payload capability of this booster is 29,800 lb.

SPACECRAFT ANALYSIS

The exploitation of the AAP cluster spacecraft subsystems provided the manned OTES conceptual design with a number of ready-made subsystems requiring little, if any, modification for direct application to OTES. These include the life-cell and environmental control (and EVA management) systems of the LM and CSM; structures; electrical; guidance, navigation, and control; data management; communications; recovery; orbit propulsion; and attitude-control subsystems.

Preferred Concept Description

Primary structural elements of the preferred OTES conceptual design are a support cone, fixed and movable cylindrical barrel segments, electro-optical equipment bay, center-of-gravity positioner, and mirror and figure sensor supports. Secondary structures include the magnetic suspension system, support rack and engagement mechanisms, free-float positioner mechanism, launch support cage, and the cable extension system. Figures 2, 3, and 4 show primary elements of the OTES conceptual design. The support cone and integral ring assembly are substituted for the inner gimbal ring of the ATM and provide the primary method of attaching the OTES spar to the rack, which in turn is mated to the LM. The telescope spar comprises a fixed cylindrical barrel segment attached to the ATM rack via the support cone ring structure and six smaller-diameter cylindrical barrel sections, which are concentrically arranged for extension, with the smallest segment extended farthest out from the gimbal. The large barrel segment houses the 2-m primary mirror for the telescope. The movable segments are pulled from the launch position by a cable extension system (stowed position, 104 in. long; extended position, 391 in.) of pulleys and cables operated by two electrical motors. Each joint of the extended spar is secured by pyrotechnic-operated pin drivers; locking of the joint forms a light-proof

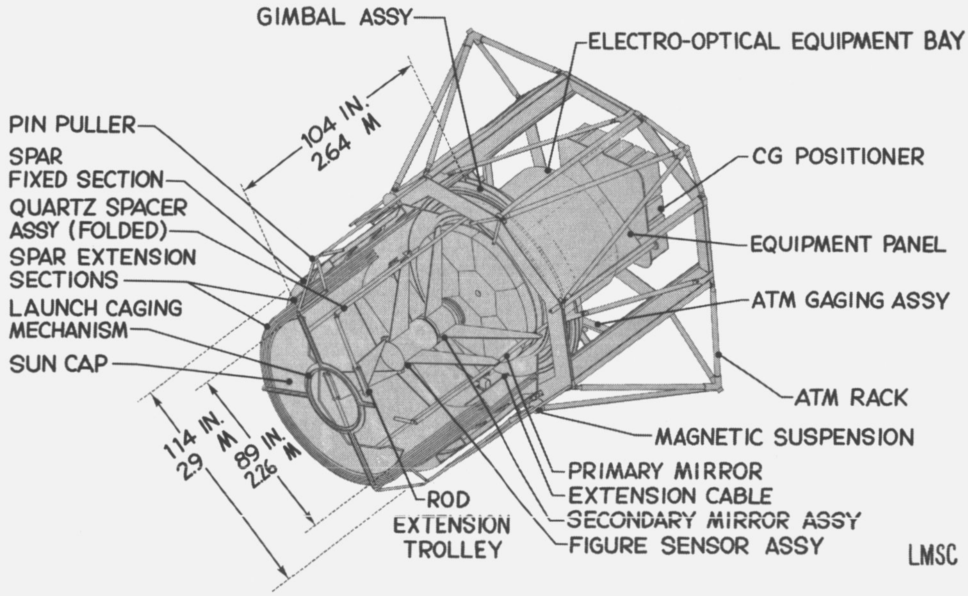


Fig. 3 OTES 2-m Concept, Stowed Configuration

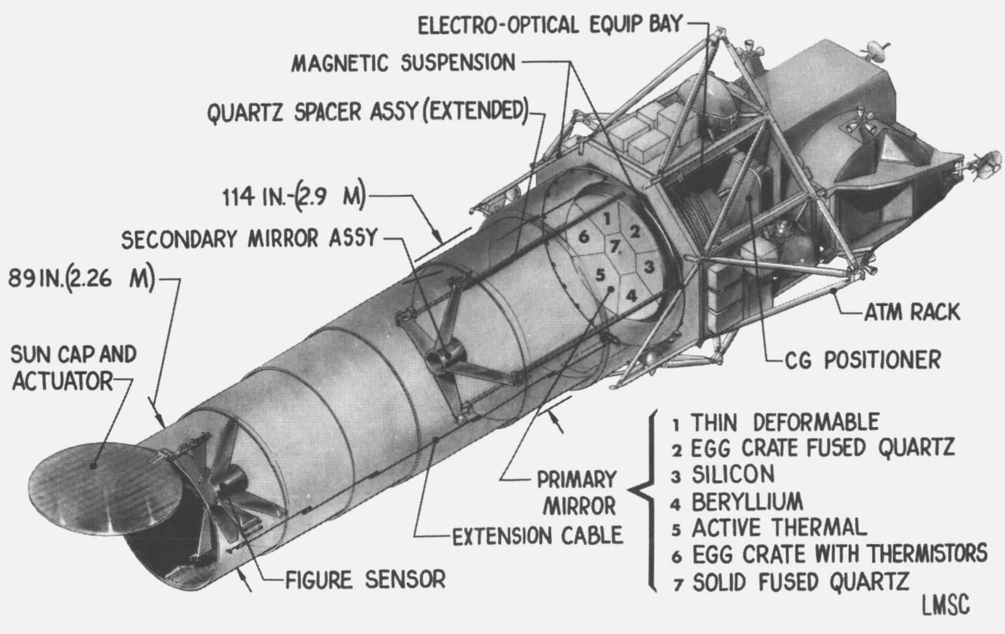


Fig. 4 OTES 2-m Concept, Extended Configuration

rigid junction. Electro-optical equipment associated with the OTES are mounted in the electro-optical equipment bay. Six of the pie-shaped equipment modules can be removed and replaced by astronaut extravehicular activity (EVA).

One of the experiments of the OTES is to demonstrate a magnetic suspension system that would replace the ATM gimbal. To effect transfer from the three-axis gimbal, the free-float positioners (bracket and linear actuators) disengage the spar from the gimbal ring and position the telescope within the magnetic suspension system torquers. The physical movement of the spar requires relocation of the center of gravity of the OTES spacecraft to the centerline of the magnetic system. This is accomplished by the center-of-gravity positioner – a ballast weight with 30 in. of travel. Primary and secondary mirror-focus distance is maintained by means of quartz spacer rods located at 90-deg intervals around the primary mirror. The rods are radially located 41.50 in. from the telescope centerline.

Passive thermal control techniques are employed to maintain internal temperature gradients to the desired operating levels. Optical surface reflectance (OSR) materials and multilayer super insulation, along with small secondary (local) insulators, constitute the passive thermal system. The AAP ATM electrical-power system provides all OTES electricity. However, a deployable (and retractable) solar-array system is needed for extended duration independent mode operations. This system most likely will be developed for the AAP independent mode operations. Earth-pointing observations would employ battery power. The AAP ATM attitude control system adequately satisfies the OTES requirements. However, star sensors (rather than solar sensors) are needed for attitude references and target location. The Apollo unified S-band communication system is used for OTES communications and data management functions. An Orbital Mirror Recoating Facility (OMRF) preliminary concept has been devised. This concept provides the capability for an EVA astronaut orbital mirror recoating experiment (Optical Technology Experiment 6). The two compartment OMRF (an airlock chamber and a vacuum chamber) would be docked adjacent to the OTES on a multiple docking adapter (MDA) docking port.

The estimated weight of the OTES/OMRF package, to be launched by a single Saturn booster, is 29,135 lb, i.e., leaving a margin of 665 lb.

Support Analyses

During the Phase II study, supporting analyses were performed in the areas of thermal, attitude control, power, dynamics/stress, astronaut requirements, and reliability/safety analyses. These studies, within the limitations of conceptual design, indicated the selected OTES approach is fully compatible with the AAP ATM concept for both the clustered and independent modes of operation contemplated for the AAP program. The OTES is limited for low-orbit earth-pointing operations; i.e., limited time exists for observation, and rate of change of the line of sight (LOS) with respect to a single point on earth becomes quite high as the spacecraft approaches the overhead position. The dynamics/stress analysis indicates the extended spar design will demonstrate sufficient rigidity to maintain critical optical tolerances.

ASTRONAUT-PARTICIPATION ANALYSIS

The Phase II astronaut participation analysis has examined potential astronaut involvement in specific representative OTES experiments to determine required behavior modes and appropriate training and facilities required to assure their development. Crew participation in the experiments has been identified to the extent possible and constraints and guidelines for crew safety evaluated. Primary emphasis has been on the EVA modes of operation and the impact of manned participation on the OTES conceptual design. A primary rule has been to commit the crew to EVA operations only when necessary, i.e., where functions can be automated the crew provides onboard monitoring and/or control only. This consideration has led to elimination of a Phase I concept in which the astronaut EVA would be used in telescope extension in favor of the preferred automatic extension technique. This, in turn, led to utilization of astronaut participation only in necessary system maintenance and experimental operations. Figure 5 illustrates a typical astronaut EVA application. Essentially, however, the Phase I manned participation study results remain valid. Use of experimental EVA objectives

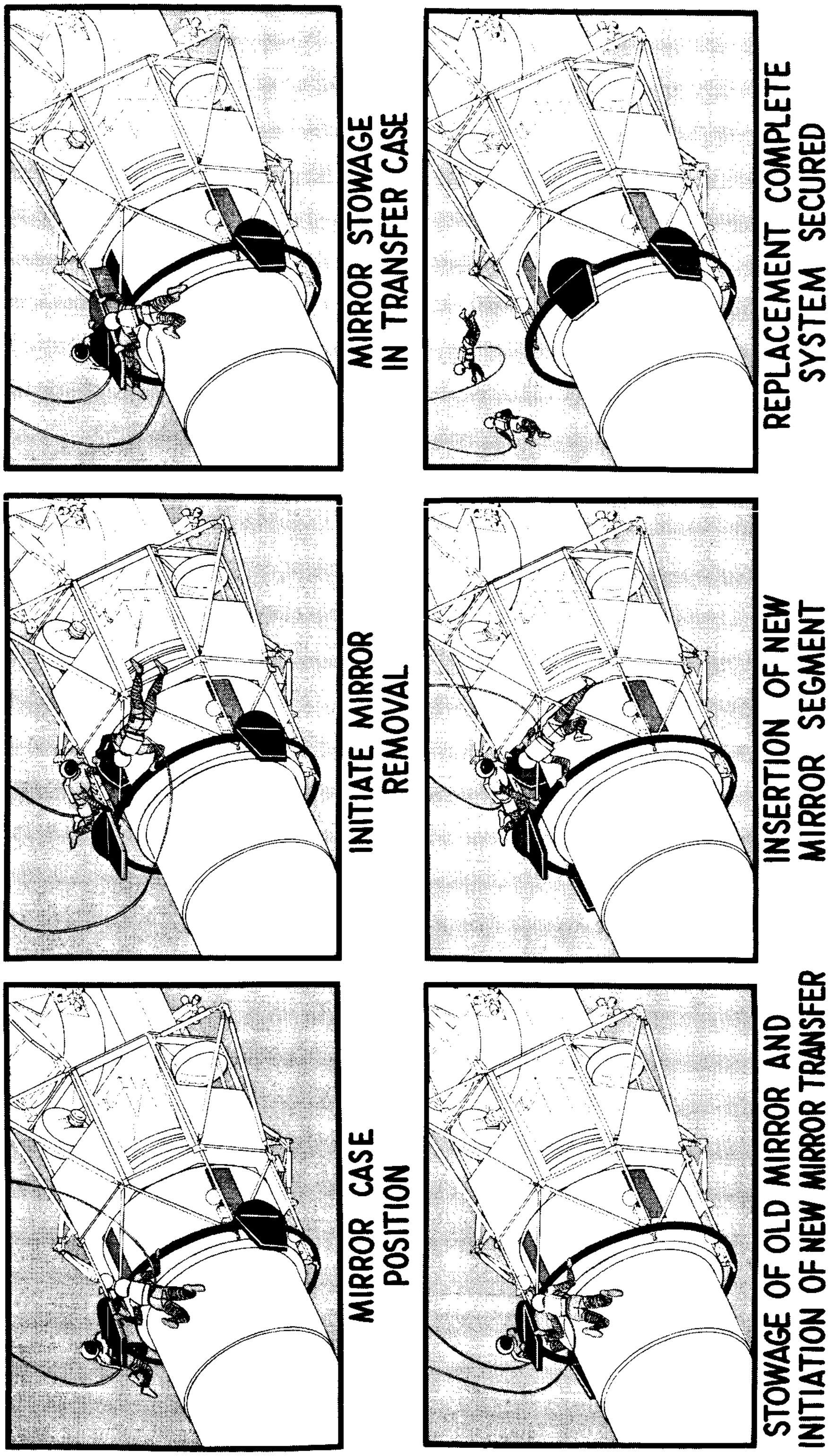


Fig. 5 Mirror Segment Removal Experiment

as analytical samples has provided an indication of the type and extent of training required to develop behavioral responses. Many of the required facilities are readily available from the AAP and Apollo training programs and in existing LMSC facilities and zero-g simulator devices.

RELIABILITY AND SAFETY ANALYSIS

The reliability goals established by NASA for AAP cluster operations can be fully met through extensive use of redundancy and spares for the basic AAP equipment supporting the OTES mission. Adherence to established NASA guidelines and constraints for astronaut safety will assure compliance to safety objectives. The LMSC Systems Effectiveness Tradeoff Analysis (SETA) technique will be used in subsequent phases of OTES development to update the Cluster A (and Cluster X) reliability apportionments with the telescope system included and to determine anticipated resupply requirements to assure reliability goals are met. This technique permits selection of optimum system designs around such factors as weight, cost, maintenance time, safety constraints, and single-point failure requirements. The technique involves a mathematical model and computer analysis to determine appropriate reliability improvements as a function of weight, cost, and maintenance time penalties.

MISSION SEQUENCES/LAUNCH CONSTRAINTS

An analysis of the launch constraints and mission sequences for OTES has been given preliminary consideration for mission planning purposes. The launch requirements to establish a Cluster X OTES experimental laboratory have been examined for launch constraints to permit cluster assembly using the proposed mission sequences for AAP ATM operations, and it has been concluded that the selected conceptual design approach is compatible with operational mission requirements. Figures 6 and 7 show the OTES spacecraft operations sequence.

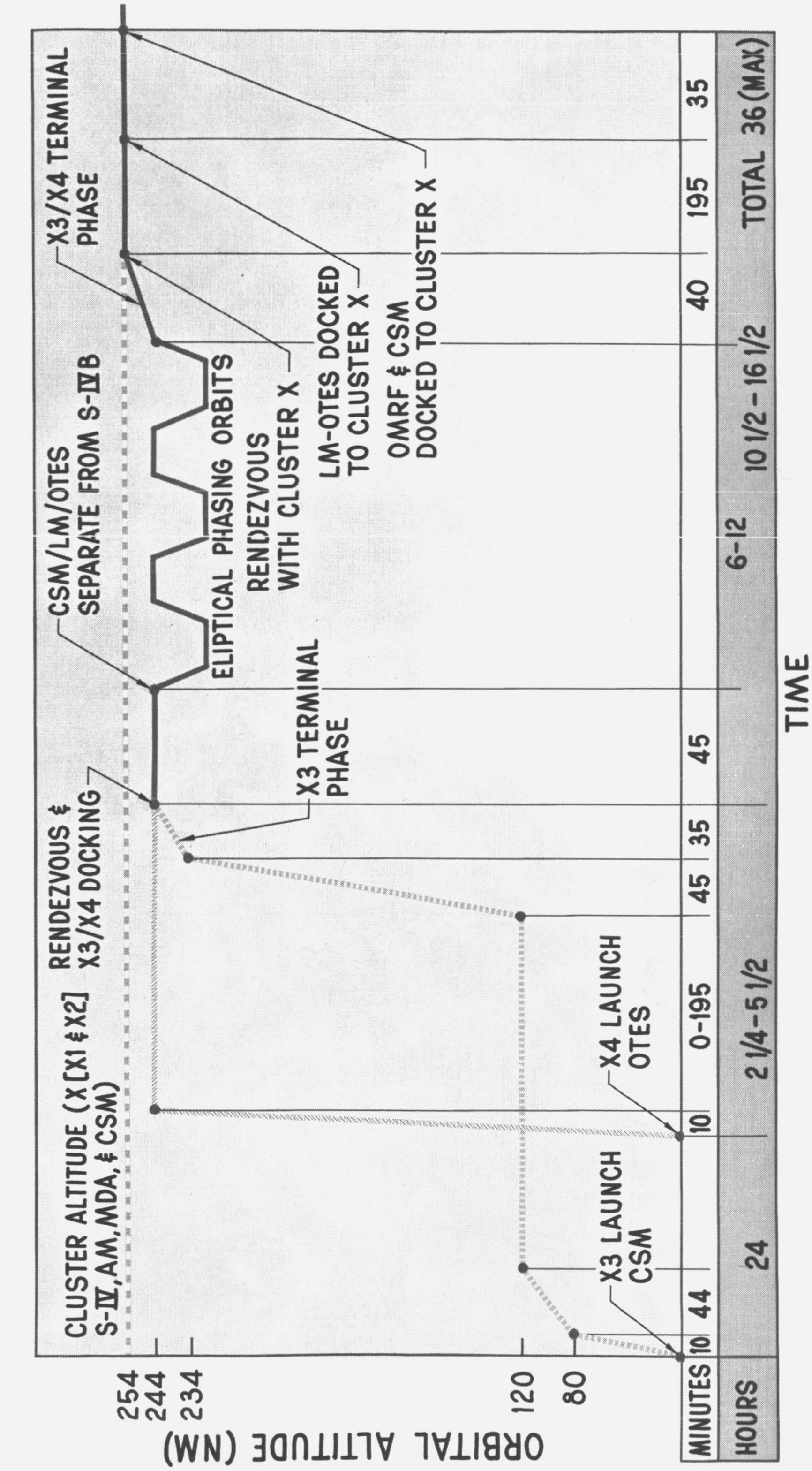
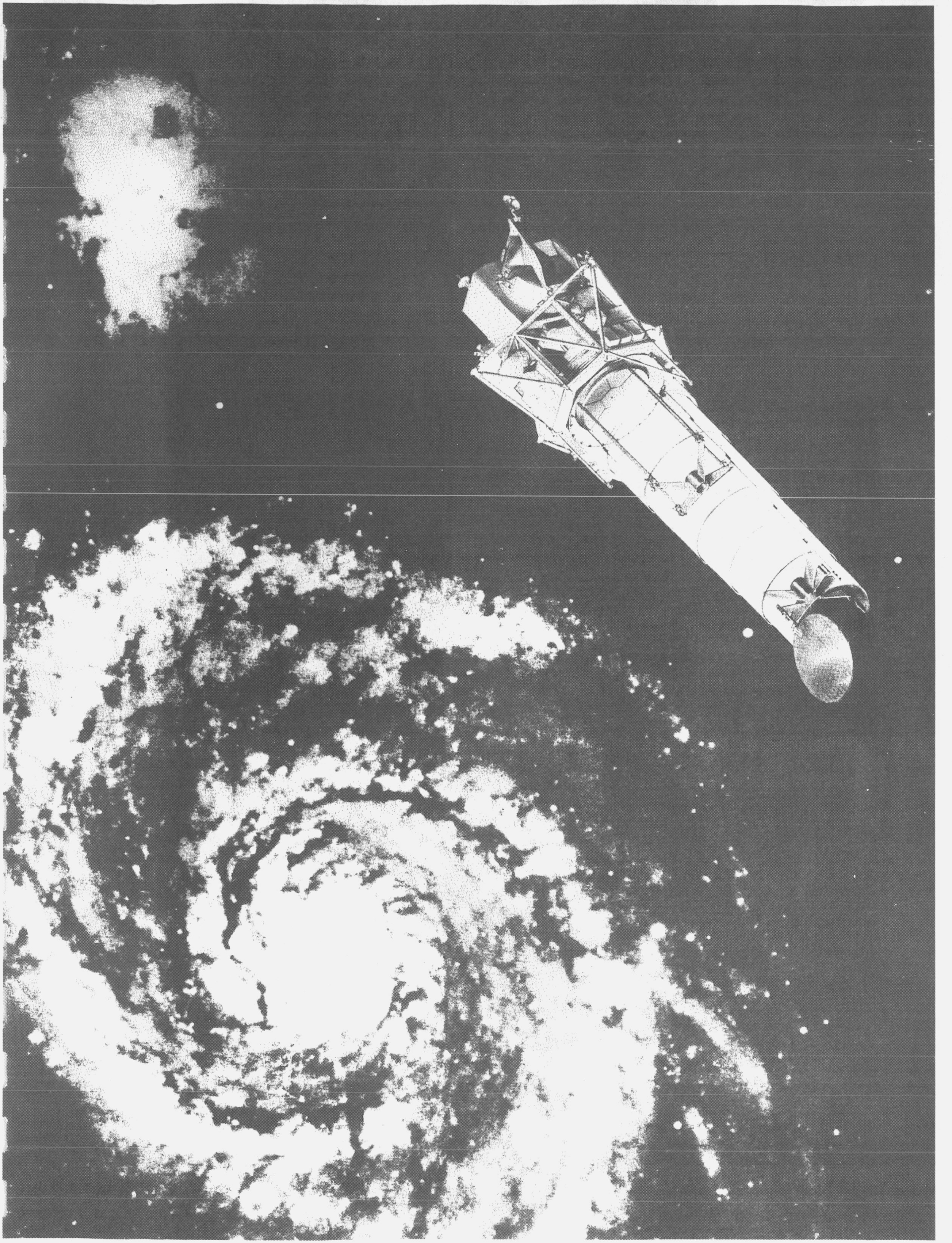


Fig. 6 Mission Profile



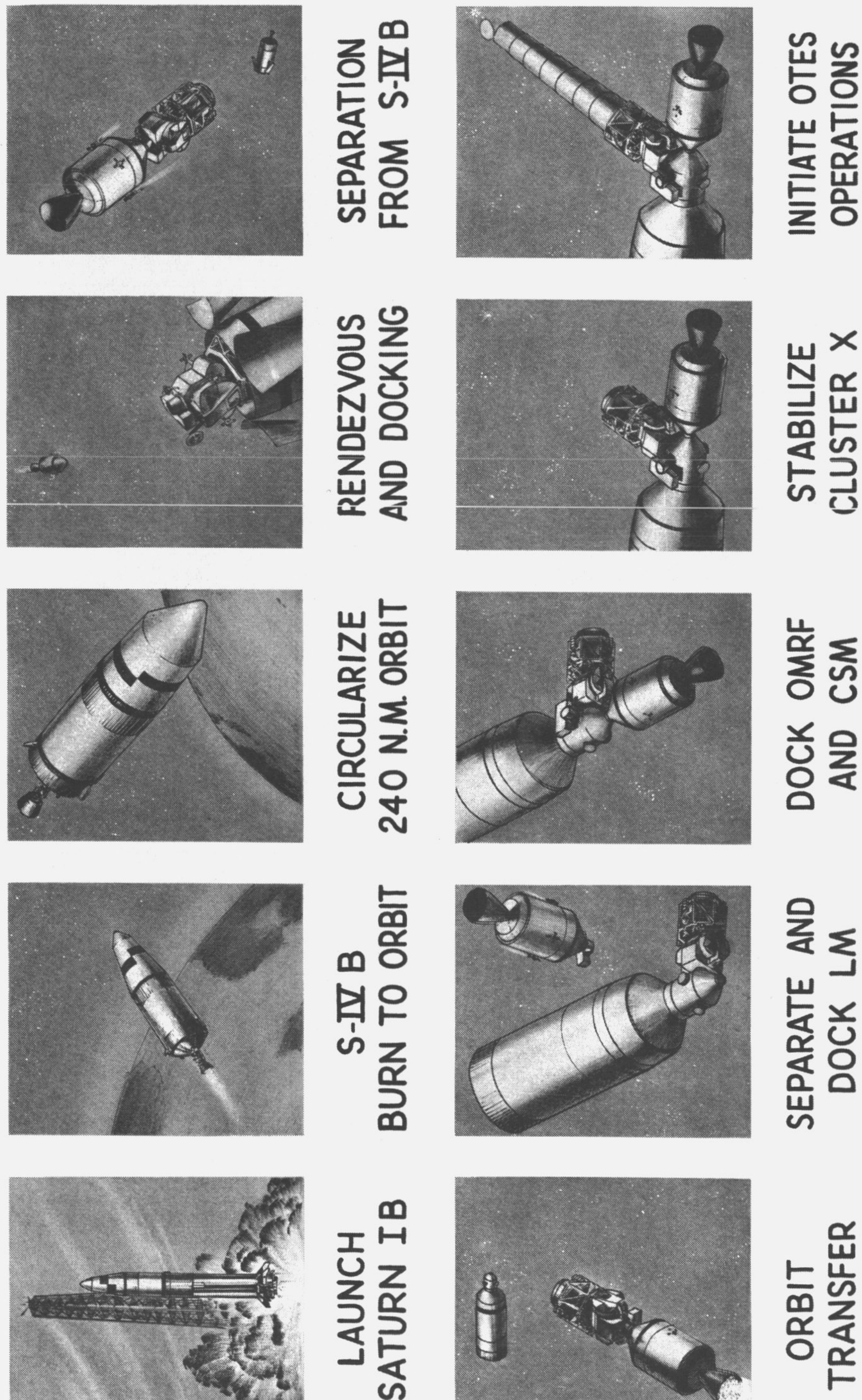


Fig. 7 Operations Sequence

RESOURCES PLANNING

Preliminary estimates of technical, facility, test, schedule, and cost requirements for OTES have been completed to a level consistent with Phase II conceptual design. Analyses and preliminary plans for each of these areas have been completed, although they must be considered as "best current estimates" rather than a firm LMSC cost proposal. The resources plans cover the OTES spacecraft and directly related development efforts. Also included are an identification of OTES/AAP integration requirements and definitization of requirements for optical subsystem developmental interface scheduling. These plans indicate that the pacing item to assure a July 1973 launch date is the electro-optical subsystem and related experimental program development. Figures 8 and 9 are the preliminary master schedule and cost summary, respectively. This cost summary includes design, manufacturing, and development testing of the telescope primary and secondary spacecraft structure. This summary specifically excludes the following costs: NASA inhouse, AAP payload integration, launch range, NASA test facilities operation, related supporting technology, primary and secondary optics, and electro-optical subsystems. In some cases, portions of the AAP costs are presented for comparison but do not appear in the OTES program cost summary.

CONCLUSIONS AND RECOMMENDATIONS

Following is a summary of major conclusions and recommendations resulting from the Phase II OTES conceptual design studies presented in this final report:

Conclusions

- The baseline spacecraft concept fully accommodates the selected OTES experiments identified by Perkin-Elmer for the OTES mission.
- The concept facilitates integration of a full 2-m diameter primary mirror (which may be either segmented or solid) telescope into the ATM rack and into the AAP operational scheme.
- Passive thermal control system techniques will maintain the primary mirror temperature gradient to less than 1°C and provide thermal control to maintain the mirror operating environment near the desired -80°C.

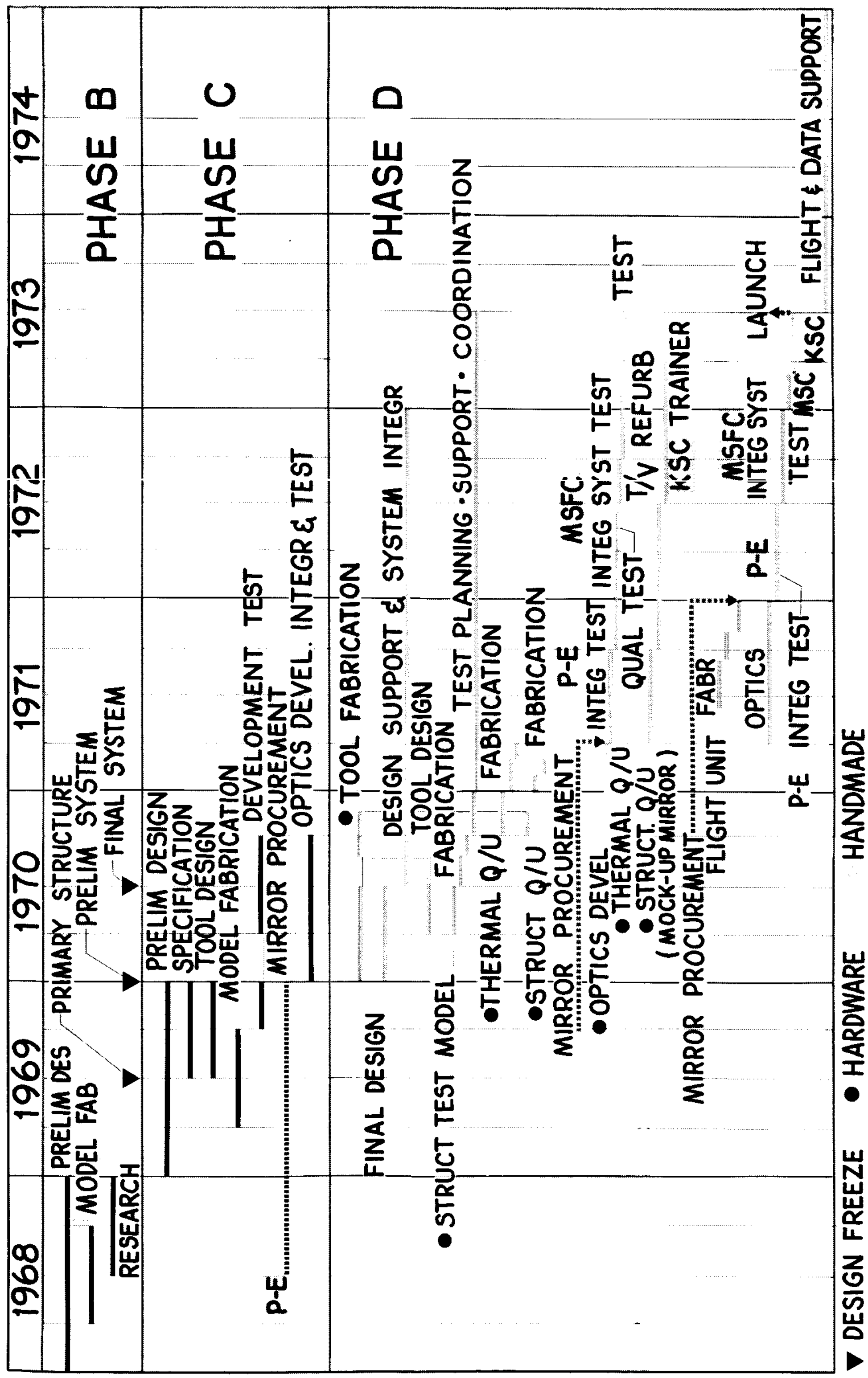


Fig. 8 OTES Program Schedule

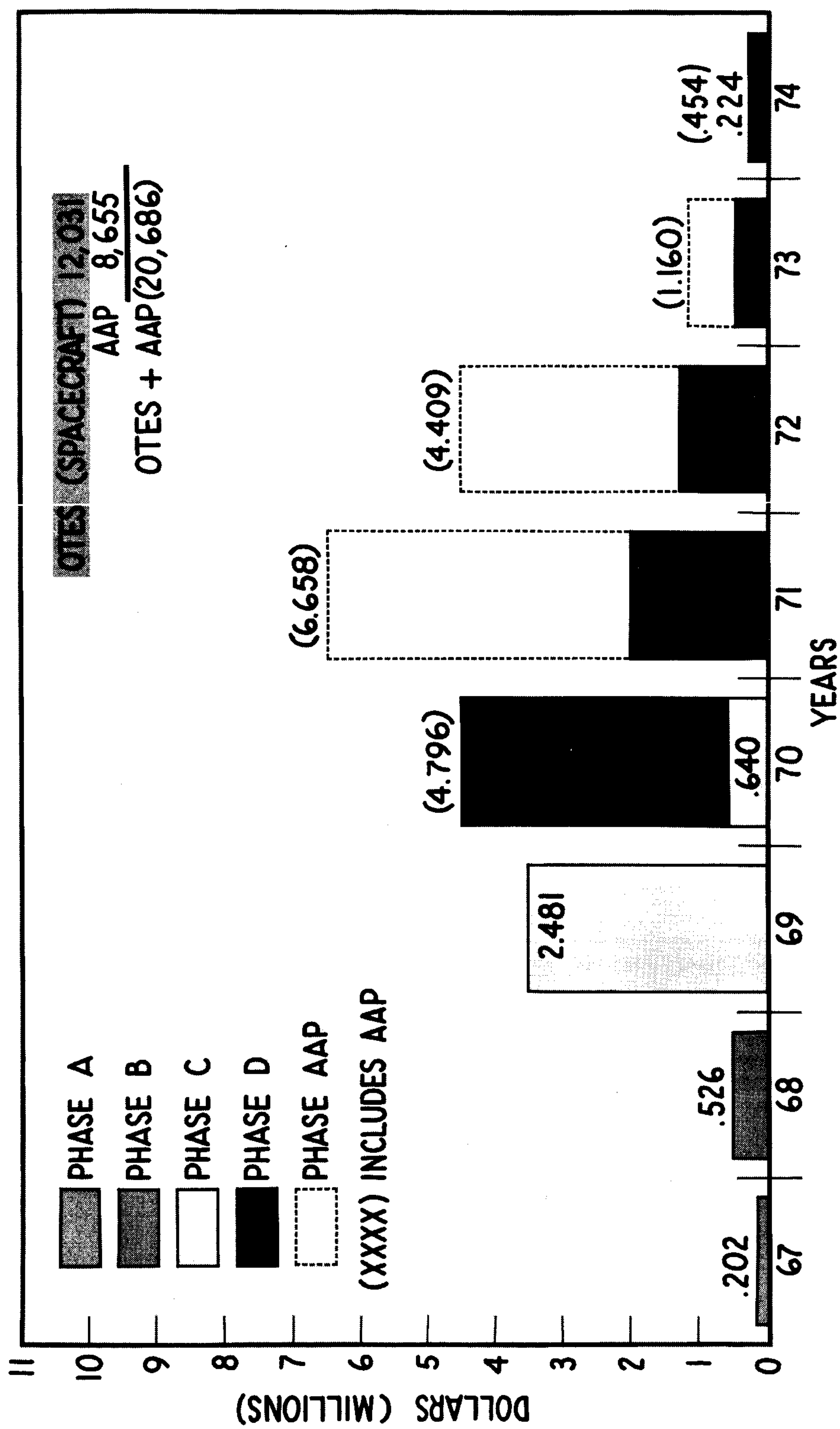


Fig. 9 OTES Spacecraft Cost Summary

- Evaluation of the AAP subsystems and performance specifications (i.e., power, communications, stabilization, pointing, etc.) indicates adequate capabilities exist to support the OTES spacecraft orbit operations in either the cluster or independent mode configurations.
- Only minor modifications to AAP subsystems are required to satisfy OTES applications.
- OTES 2-yr life goal attainment requires astronaut maintenance and resupply.
- Astronaut task development (simulation and tests) is highly desirable during Phases B, C, and D of the OTES Program.
- Existing and proposed AAP facilities are adequate for OTES Program needs.
- Mid-1973 launch can be accomplished within the OTES conceptual design approach.
- Conceptual design efforts during OTES Phases I, IA, and II (Phase A) have enabled selection of a "preferred concept" prior to initiation of formal Phase B preliminary design activities.

Recommendations

- The preferred OTES concept selected during Phase II studies should be refined and developed further in preliminary design (Phase B) activities.
- In the process of advancing the design level from conceptual to preliminary design phases:
  - Major emphasis should be on electromechanical operating mechanisms, primary and secondary structures, and passive thermal-control design details.
  - Minimum efforts are required on AAP spacecraft subsystems until the AAP subsystem configurations are established firmly.
- A vigorous program of tests and simulations should be undertaken to establish firm astronaut "task" development data required for design, operational, and safety considerations.

CHAPTER 1 - SUMMARY

In order to proceed with the simple formulation of an objective for a technology oriented program in space optics, it is necessary to step well back from the details of the program. There are two basic questions which must be answered by NASA management:

Where is the U. S. going in space?

What prospective national goals require new space optics?

If the answer to the first question includes the concept of the "exploration of space", then the answer to the second question must include the two areas of space astronomy and planetary probes. And, it is in these two areas that the major source of the proposed optical technology experiments in space are found. If the reader agrees to the twin concepts of "exploration" and "new space optical technology" presented above, then the justification for an optical technology flight program is established.

Space astronomy and planetary probes represent two fundamental tools required for the exploration of space. The development of these tools requires new space optical technology in order to satisfy the future mission needs of NASA. Space astronomy requires the new optics associated with resolution performance not obtainable on earth in both angle (large diffraction-limited optical systems) and wavelength (ultraviolet and infrared). Planetary probes require new high data rate laser communication systems in order to conduct successful experiments in the vicinity of the planets. Thus, by understanding the nature of the future NASA missions requiring new space optics, the objectives of the OTES can be clearly formulated.

The objective of the OTES is the performance of scientific and engineering space experiments which advance space optical technology in support of future NASA missions.

The proposed experiments and the integrated experiment system fall in broad, yet systematically related, categories:

- Optical Technology (diffraction-limited performance of large apertures and fractional arc-second guidance)
- Optical Communication and Tracking (with deep-space emphasis)
- Effects of Aerospace Environment (on optical technology and laser communication problems)

Forty-four experiments, including applications, have been identified and approximately thirty optical technology experiments were studied in detail. Five different system concepts were evolved and examined for feasibility within the restraints and guidelines of the specification.

PRINCIPAL PROGRAM CONCLUSIONS OF THE PHASE A STUDY

SPACE OPTICAL EXPERIMENTS

As a consequence of three years of study of space optical experiments, Perkin-Elmer in consort with NASA specialists have arrived at the following position:

1. There are worthwhile flight optical experiments.
2. Apollo vehicles can be justified for a manned space optical laboratory.
3. 2-Meter and 3-Meter aperture telescopes and the optical experiments with spacecraft are technically feasible.

The first principal conclusion is supported by the experiments presented in Chapter 2. Specifically, after approximately two years of study and in the current study, NAS8-20255, one year of effort through Contract NAS8-11408 (Determination of Optical Technology Experiments for a Satellite), the list of prospective space experiments has grown in some areas and has been reduced in other areas. Perkin-Elmer recommends the following space experiments in optical systems to NASA:

OTES EXPERIMENTS

1. 2-METER ACTIVE OPTICS	17. (DELETED)
2. SUPER COLD TELESCOPE	18. (DELETED)
3. ASTRONAUT UTILIZATION TESTS	19. 1/10 ARC-SECOND TRACKING
4. FIGURE MEASUREMENT/SCATTERPLATE	20. POINT AHEAD
5. FIGURE MEASUREMENT LASER	21. ACQUISITION
6. MIRROR COATING	22. EARTHSHINE/ACQUISITION-TRACK TESTS
7. THIN MIRROR	23. LASER COMMUNICATION
8. ACTIVE THERMAL CONTROL	24. RLOS
9. 1/100 ARC-SECOND POINTING	25. TRACKING TRANSFER
10. OFF-AXIS MEASUREMENTS	26. SUSPENSION SYSTEM
11. RADIATION/PMT TESTS	27. CALIBRATION LOOP
12. FIGURE/TEMPERATURE	28. SCINTILLATION
13. ALIGNMENT/TEMPERATURE TESTS	29. ABSORPTION
14. FIGURE/EARTHSHINE TESTS	30. HETERODYNING (EARTH)
15. RADIATION/OPTICAL TESTS	31. HETERODYNING (SPACE)
16. (DELETED)	32. POLARIZATION
34. OPTICAL SCATTERING ENVIRONMENT	33. CLEAR AIR TURBULENCE

We believe that these are important space optical technology experiments that can best be conducted from a space vehicle. Some of the proposed experiments can only be conducted from a space vehicle. From the broad program point of view, it is the Perkin-Elmer recommendation that two flights be conducted: one for the laser communication experiments and a second flight for the large optics experiments utilizing a 2-meter aperture telescope which could function at a low orbit (260 mile).

JUSTIFICATION FOR FLIGHT EXPERIMENTS

There is no argument with the concept that optical systems will contribute significantly to the exploration of space. The underlying philosophy of the OTES Program is that space optical technology* will be advanced to a position of timeliness by the conduct of scientific and engineering experiments aboard an Earth-orbiting vehicle. The thoroughly engineered optical spacecraft test bed with complete instrumentation will not only advance optical technology, but is economically sound. Future optical missions, whether space observatories with giant telescopes or deep-space probes with laser communication links, are orders of magnitude more expensive than the proposed optical experiments.

The justification for the OTES Program concept stated as simply as possible is: THE CONDUCT OF SELECTED OPTICAL EXPERIMENTS ABOARD A SPACECRAFT IS THE TIMELY AND ECONOMIC METHOD OF DEVELOPING SPACE OPTICS.

The technical data that the 2-meter OTES flight would provide is summarized below:

2-METER OTES JUSTIFICATION

PROVIDE NASA WITH DATA FOR NATIONAL SPACE OBSERVATORY

- ORBITAL ALTITUDE DECISION DATA
  - DAYLIGHT ASTRONOMY
  - POINTING DISTURBANCES
  - THERMAL BALANCE
- MANNED SPACE ASTRONOMY TECHNIQUES
  - ERECTION
  - ALIGNMENT
  - MODIFICATION
  - MAINTENANCE
- PRIMARY MIRROR EVALUATION
  - ACTIVE OPTICS
    - SEGMENTED TESTS
    - DEFORMABLE TESTS
    - THERMAL TESTS
  - MATERIALS
    - QUARTZ
    - SILICON
    - CERVIT
    - BERYLLIUM
- POINTING DEVELOPMENT
  - TRANSFER LENS
  - FREE FLOAT
  - FLEXURE GIMBALS
  - CLUSTER – AUTONOMOUS MODES

---

*"...preeminence in aeronautics and space in the future certainly demand a continuous evolvement of new technology. The consequences of not having done our homework prior to undertaking a system development to meet an explicit requirement are overruns in cost and time. These costs and resources are often so high that the means must be found to evolve new technology in advance of requirements." R.I. Bisplinghoff at the Air Force Association Meeting, March 15, 1967.

OTES PROGRAM PLANS

In the implementation of the technology oriented program in space optics, the spectrum of flight possibilities varies from the concept of conducting a myriad of small individual flight experiments on orbiting vehicles of opportunity to the concept of designing a special flight vehicle tailored exclusively to the optical technology experiments and conducting all of the experiments aboard a single flight vehicle. In the OTES Phase A study, these possibilities were reviewed and the recommendation of Perkin-Elmer and Lockheed is that the laser communication experiments be conducted independent from the flight system for the large optics experiments. The payload for the laser experiments must be at a 22,000 mile orbit while there is considerable benefit from conducting the large optics experiments at altitudes below 500 miles as noted on the previous page.

The program concept of the 2-meter OTES is based on five key elements:

2-METER OTES PLAN

1. CLUSTER– 260-MILE ORBIT
2. FIT INTO ATM GIMBALS & LM RACK
3. CONDUCT OPTICAL ENGINEERING EXPERIMENTS
4. USE RESIDUAL HARDWARE 2-METER APERTURE TELESCOPE FOR ASTRONOMY
5. PROVIDE THE TECHNOLOGY FOR THE 3-METER (and LARGER) TELESCOPES OF THE FUTURE

In order to gather the data required for the laser communication area, a synchronous orbit payload is required to conduct the communication and propagation experiments. The program concept of a 0.5 meter laser/telescope flight is based on five key elements:

LASER EXPERIMENTS PLAN

1. 500 POUND LASER/TELESCOPE-SYNCHRONOUS ORBIT.
2. FITS INTO ATM GIMBALS & LM RACK.
3. CONDUCT LASER PROPAGATION EXPERIMENTS UP GOING AS WELL AS DOWN GOING ON AT LEAST 2 WAVELENGTHS.
4. USE RESIDUAL HARDWARE FOR TELEMETRY OF SCIENTIFIC OR ENGINEERING DATA FROM THE SPACECRAFT.
5. PROVIDE THE TECHNOLOGY DATA FOR DEEP-SPACE LASER COMMUNICATIONS.

Thus, data to be developed from the Laser Communication Satellite Experiments (LCSE) will be the measurements of the propagation and tracking performance of the system. In addition, the LCSE will verify the operation of key subsystems and components by telemetry of diagnostic data. The key parameters to be measured at the ground receiver telescope at the OTTOS* site are:

- Measurement of laser propagation data through the entire atmosphere in the form of received signal power and operating SNR. The average signal-to-noise ratio is approximately 30 db for daytime operation at 60 degree zenith angle based on radiated power outputs of 3 milliwatts from a spaceborne helium-neon laser.

- Measurement of 10^6 and 10^7 bit/second data and measurement of probability of bit error rates (fade statistics).

- Measurement of 0.1 arc second laser beam pointing by the laser telescope to the earth receiver station.

- Evaluation of received video data, i.e., TV picture to establish realistic fade margin requirements for quantum limited photon communication channels.

SPACE OPTICAL TECHNOLOGY PLAN FOR NASA

One of the most difficult problem areas in the current OTES study was the broad question of recommendation to MSFC and OART of an optical technology plan with appropriate flight experiments at suitable times. The plethora of concepts had to be sifted and sorted to search for that recommendation which would represent a good buy for NASA. The recommendation would have to stand the test of acid scrutiny in the area of satisfying the future needs of NASA in the most economic manner. The interdependence of the two proposed flights and the data that they would bring to the propsective national goals of the U.S.A., are inherent in the Perkin-Elmer recommended NASA SPACE OPTICAL TECHNOLOGY PLAN. See Figure 1.

The KEY FEATURES of the Plan are:

1. Two flight experiments.

   - Laser Satellite Experiment launched to synchronous orbit in 1971 for the development of laser propagation data. (Figure 8, page 15).

   - 2 Meter OTES Telescope launched into low orbit in 1973 as part of the AAP Cluster. This instrument would be designed to conduct experiments in large optical technology and act as a test bed before committing significant funds to the development of a 3 Meter Telescope. (Frontispiece.)

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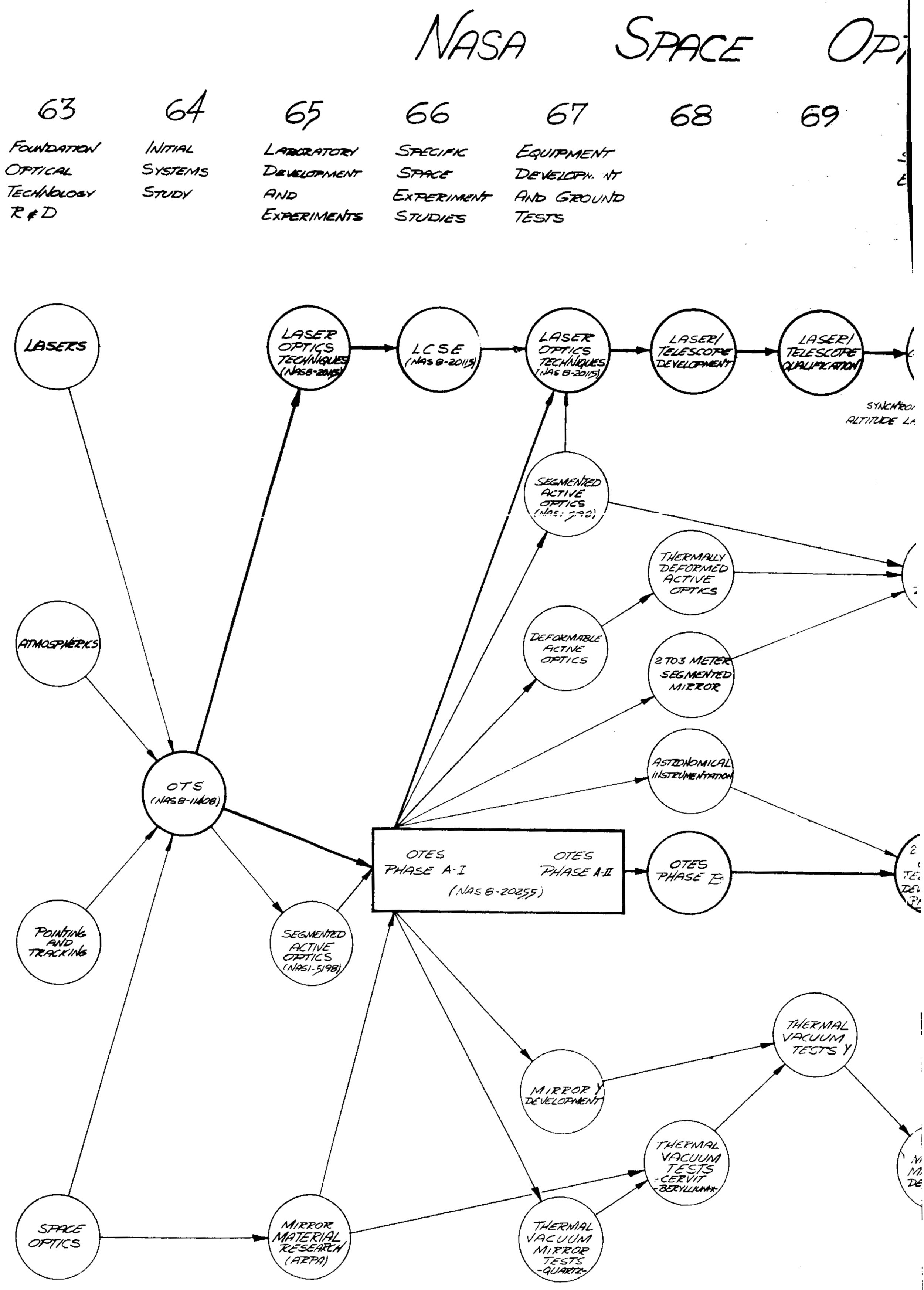
*Optical Technology Test and Operations Site (See Chapter 5).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:S TECHNOLOGY PLAN

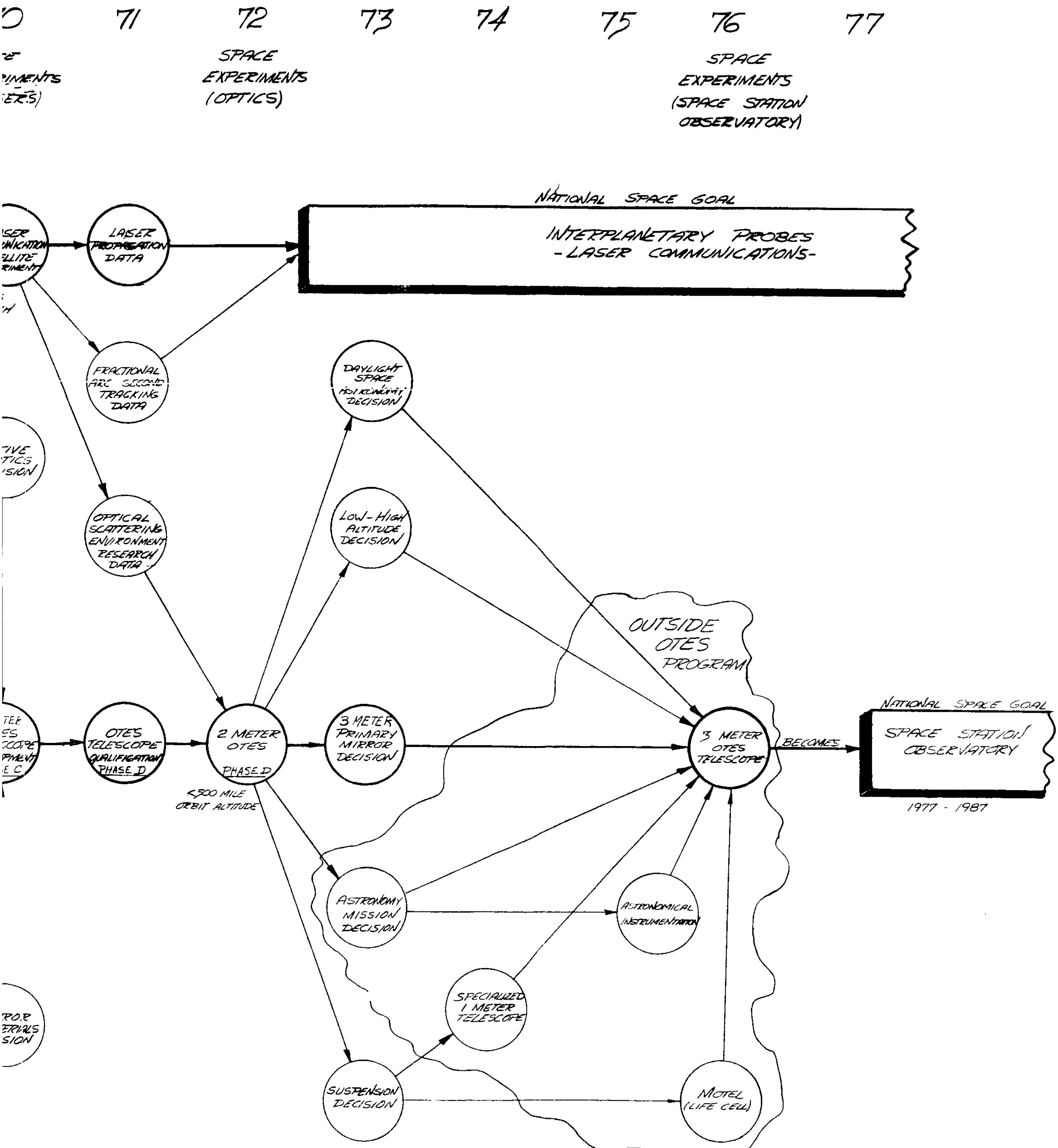

Figure 1

The EQUIPMENT BUDGET RECOMMENDATIONS to Implement This Plan are:

Supporting Technology (1968-1972)	$8 million
Laser Satellite Experiments at synchronous altitude in 1971	7.5 million
2 Meter OTES Telescope as part of AAP Cluster at a low altitude in 1973	42 million
Total	$57.5 million

The BASIC ADVANTAGES AND/OR DISADVANTAGES TO NASA are:

- Timely technology development.
- Conduct appropriate space experiments to develop the necessary data to provide answers to key questions:

  1. Up and Down going laser propagation data.
  2. Daylight astronomy feasibility.
  3. Low-High orbit for space observatory.
  4. Optimum primary mirror for space observatory.
  5. Optimum suspension technique for future telescopes.

PRINCIPAL TECHNICAL CONCLUSIONS OF OTES PHASE A

As a consequence of the efforts of the Perkin-Elmer/Lockheed OTES Team during the Phase A of the OTES Program, there have been important computations and concepts developed to precipitate advances in the space optical technology areas:

<u>Large Optics Technology Area</u> 1) An experiment system temperature of -80°C can be achieved passively for a 3-meter aperture telescope mirror at synchronous orbit and almost -80°C for a 2-meter aperture telescope in a 260 mile orbit. 2) Active Optics is an excellent area for space experiments in large optics.

<u>Thermal</u>

The temperature at which the expansion coefficient of fused quartz goes through zero is -80°C. Therefore, the effects of thermal gradients in the mirror which would tend to deform the figure of the mirror are minimized. The calculations which have been performed indicate that variation about the -80°C point of ±4.5°C would cause thermoelastic deformations of 1/50 wave, while the corresponding spacecraft calculations indicate that the mirror would have thermal gradients of less than 1°C. Thus, there is overlap between what the optical system needs and what the spacecraft can supply.

In addition to the theoretical thermal calculations, Perkin-Elmer has made the measurements of the figure deformation of a large space mirror of fused quartz to support the contention that precise thermal engineering of the space telescope is mandatory. Figure 2 shows an instrumented 32 inch eggcrate quartz mirror prior to its insertion into thermal vacuum test facility designed to measure the departure of a mirror surface in the presence of thermal gradients.

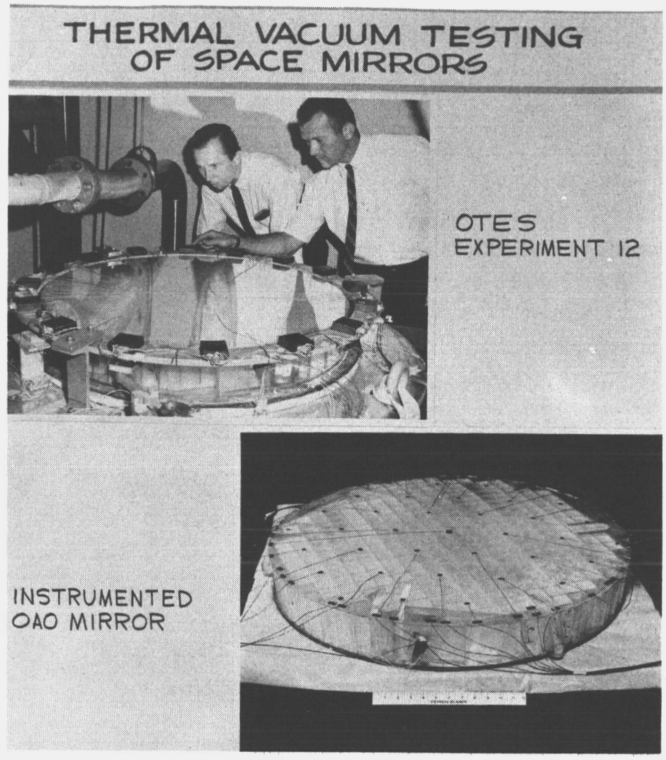

Figure 2

Scatterplate interferograms were made of this mirror while in thermal equilibrium and while the mirror was subjected to heat at the mounting points (Figure 3). Reduction of the interferometric data showed that a +6°C rise at the mounting points gave rise to a change in mirror figure of $\lambda/33$ at 20°C. This deformation can be scaled proportional to the coefficient of expansion ($\alpha \approx 4 \times 10^{-7}$ at 20°C and $\approx 0.5 \times 10^{-7}$ at -75°C); thus, the measured thermal deformation of this quartz mirror would have been less than $\lambda/200$ at the -80°C temperature.

Experiment No. 2, the Super Cold Telescope, has a temperature of -80°C specified for it. This temperature is optimum only for fused quartz #7940. The mirror segments number 1,2,6 and 7, and the spacer rods as shown in the Frontispiece are made of this material. The -80°C temperature is not optimum for those mirror segments made of Cervit (number 5), silicon (number 3), Ultra Low Expansion (U.L.E.) quartz #7971 (number 6) or beryllium (number 4). The optimum temperature for each of these materials is readily apparent by reference to the curves of allowable temperature tolerance as a function of temperature. Figure 4 shows the peaking of the tolerance at -80°C while other curves* indicate different optimum temperatures for each material (i.e., +100°C, -180°C, -160°C, -269° respectively for the materials listed above). The justification for the -80°C temperature specification for Experiment No. 2 is that this temperature provides the maximum amount of technology data consistent with the need to provide the greatest degree of technological advance and reliability for the proposed 2-meter OTES flight.

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*See Figures 48 , 49, and 50 starting on page I-100

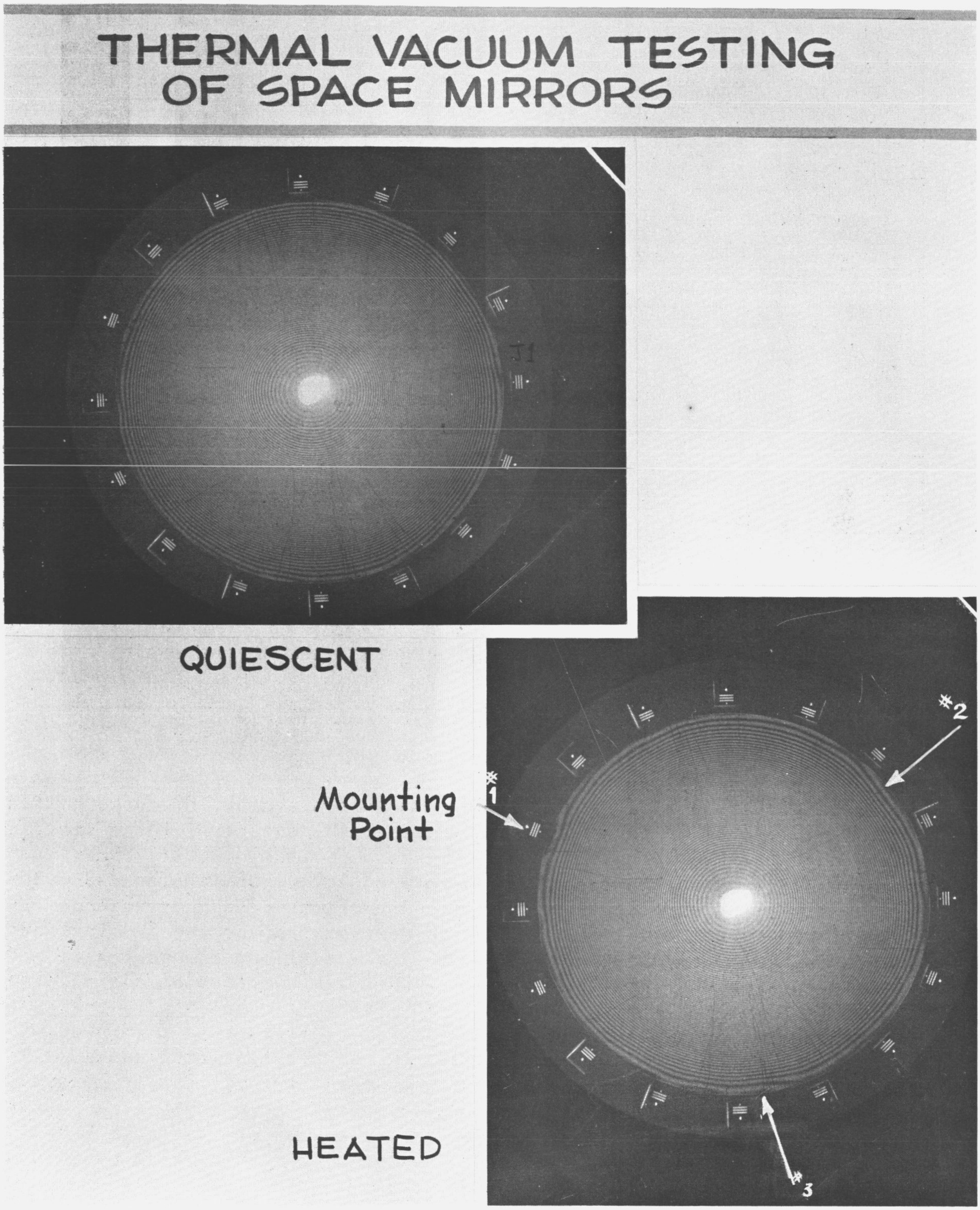

THERMAL VACUUM TESTING
OF SPACE MIRRORS
QUIESCENT
J1
#2
#1
Mounting
Point
HEATED
#3

Figure 3.

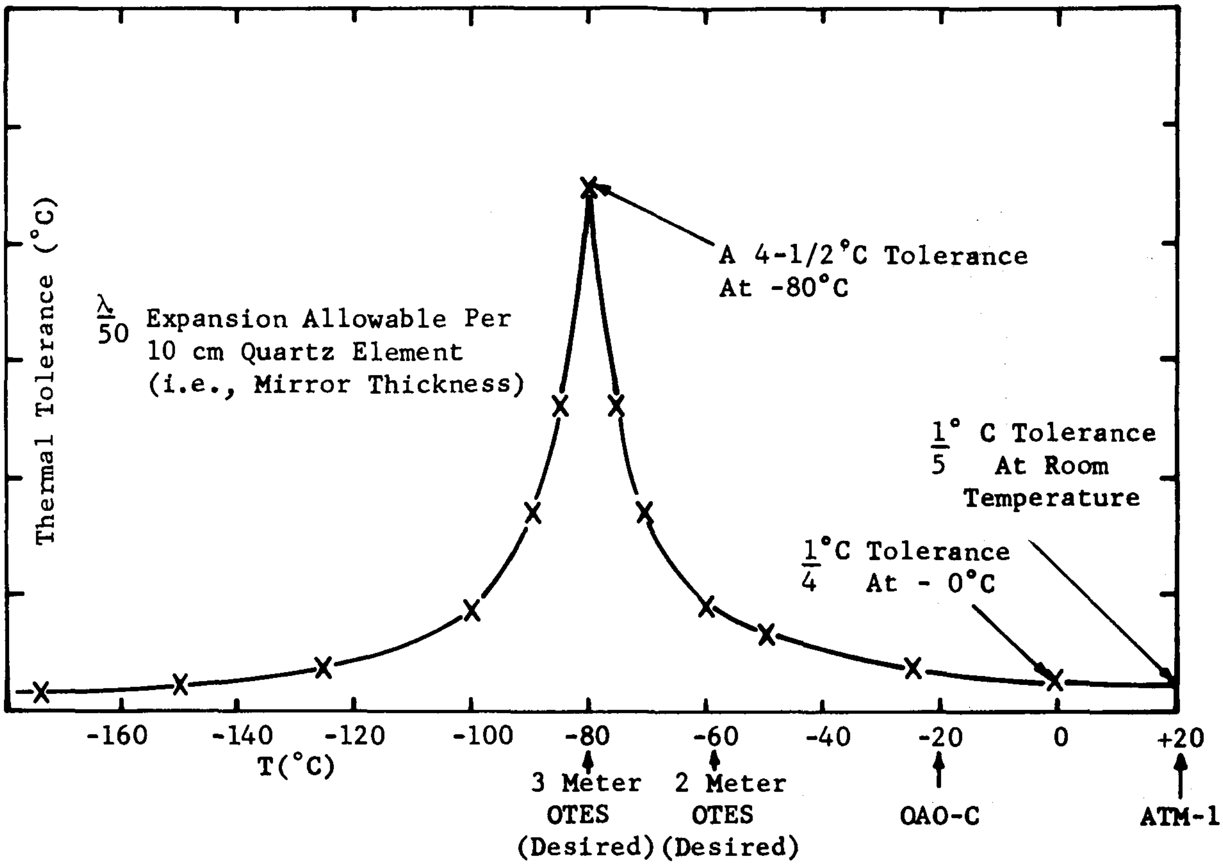


Figure 4. Quartz Mirror Thermal Tolerance

Active Optics

The Segmented Active Optics technique for the achievement of large diffraction-limited mirrors is of paramount importance to the future of large orbiting space telescopes. During the course of the OTES Study, Perkin-Elmer completed the laboratory demonstration of the Segmented Active Optics for NASA under sponsorship of Langley Research Center. The demonstration proved conclusively that a large mirror can be fabricated in sections and by the application of laser interferometry and precise servos, these sections can be positioned to the necessary precision to produce the equivalent surface of a single one piece mirror. The 20 inch, three segment mirror is shown in Figure 5 while the corresponding figure error measurement scans illustrate the power of this technique. The average figure error for the composite mirror measures at λ/40 while the corresponding figure of the segments individually measures at λ/30 average. Not only does the technique permit operation at the performance level of the individual segments, but the technique permits small - but not negligibile - performance improvements since the control system positions the segments to their optimum location.

The segmented active optics technique is capable of providing a λ/50 rms mirror of 3-meter or larger aperture in a space telescope. The deformable active optics mirror work has started at Perkin-Elmer, but there are no results to report as of this date.

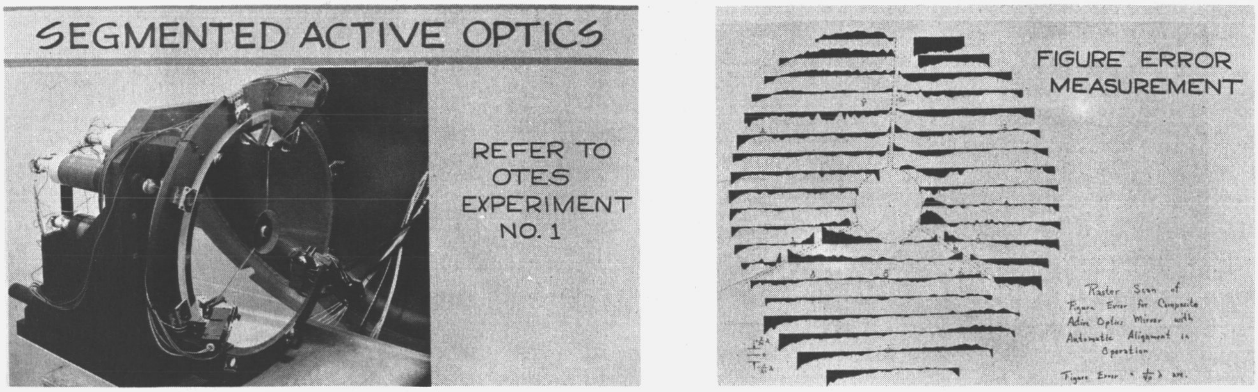


Figure 5. Segmented Active Optics

<u>Optical Communication Area</u> - The optical communication system calcuations of the OTS Study (NAS8-11408) and the Laser Optics Techniques experiments (NAS8-20115) have been reexamined, reconfirmed, and expanded.

During the present study, link calculations were made on 5300 Å lasers, helium-neon lasers, coherent and incoherent carbon dioxide molecular lasers, and sun-pumped YAG lasers for the space transmitter. These calculations confirm the high data rate capacity of deep-space optical communications system which establish laser communications as an important telemetry tool for deep-space probes.

There were ten outstanding advances during the last three years of the study in the laser communication field:

<u>December 1964:</u> The Phase I Report of the OTS was released. In this report, a complete down link communication system was conceptually synthesized which had the capacity of 1 million bits/second at an error rate of 0.001 per bit for a range of 100 million miles. Each important element of the laser/optical communication system was characterized by its key performance requirements and the techniques required to achieve the required parameters were identified. (Perkin-Elmer NAS8-11408).

<u>April 1965:</u> High quantum efficiency detectors through the use of total internal reflection were developed. (NASA-AMES Research Center.)

<u>June 1965:</u> High power and high efficiency CO_2 lasers were developed. (Bell Telephone Laboratories).

September 1965: Measurements were completed on the variations of intensity in the far field beam of a diffraction-limited single mode helium-neon laser. Fluctuations of intensity of less than 1 percent were observed. Consequently, beam intensities in the far field could be predicated on photometric calculations without applying excessive safety margins for centroid of illumination wander. (Perkin-Elmer NAS8-20115.)

December 1965: High power argon lasers were developed. These lasers replaced in principle the arrays of gallium arsenide lasers required for the ground beacon. (Raytheon, RCA, Hughes and Perkin-Elmer.)

March 1966: 10" isolation between two laser wavelengths in a common laser transmitter/receiver telescope was demonstrated in the laboratory. (Perkin-Elmer NAS8-20115.)

June 1966: 1/10 arc second laser beam pointing was demonstrated in the laboratory. The transfer lens used in the demonstration is shown in Figure 6 with the laser telescope in Figure 7. Figure 8 shows the complete laser/telescope designed to conduct the laser communication experiments from a satellite.

August 1966: The technical announcement of a very narrow band high transmission Fabry-Perot tunable filter appeared in Applied Optics. (National Standards Laboratory SCIRO, Australia.)

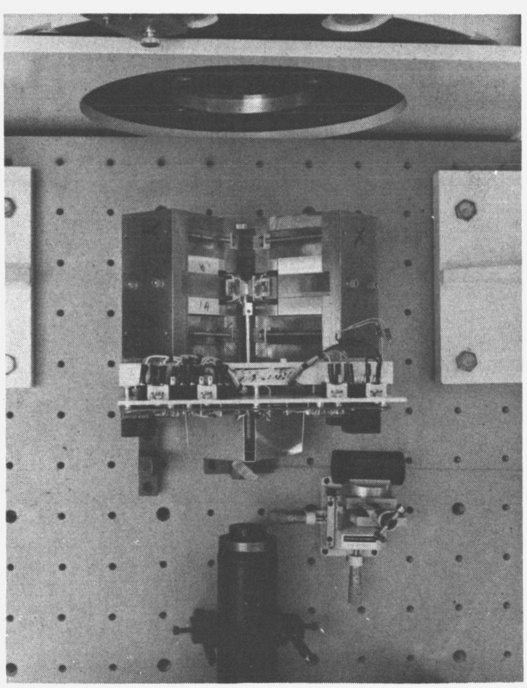


Figure 6. Transfer Lens

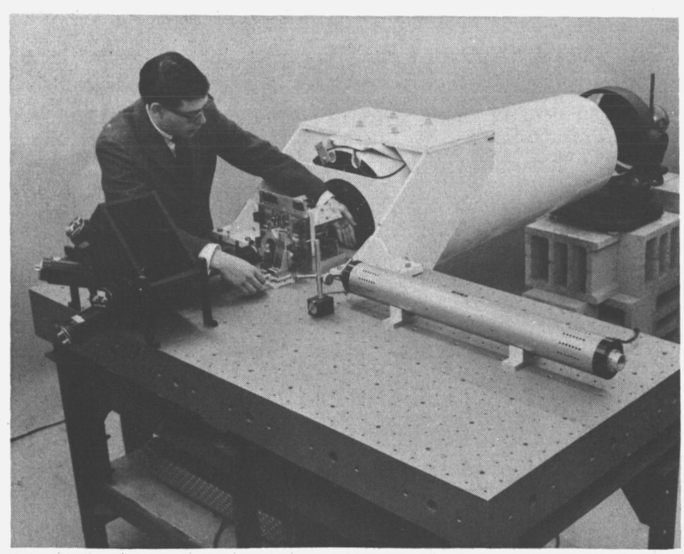


Figure 7. Laser Telescope

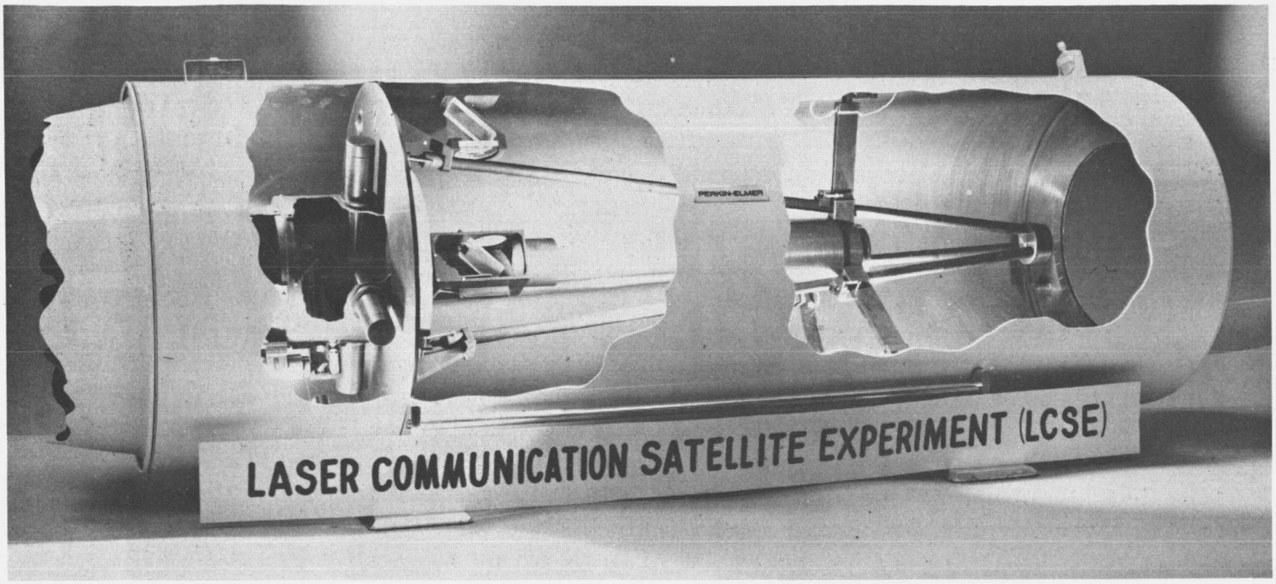


Figure 8.

October 1966: Point ahead of a laser beam demonstrated in the laboratory using Risley prism servo systems. The Risley prism point ahead assembly used in the demonstration is shown in Figure 9 and the physical arrangement of the apparatus behind the telescope appears in Figure 10. (Perkin-Elmer NAS8-20115.)

November 1966: Announcement released of high power CW 5300Å laser with high efficiency. (Bell Telephone Laboratory.)

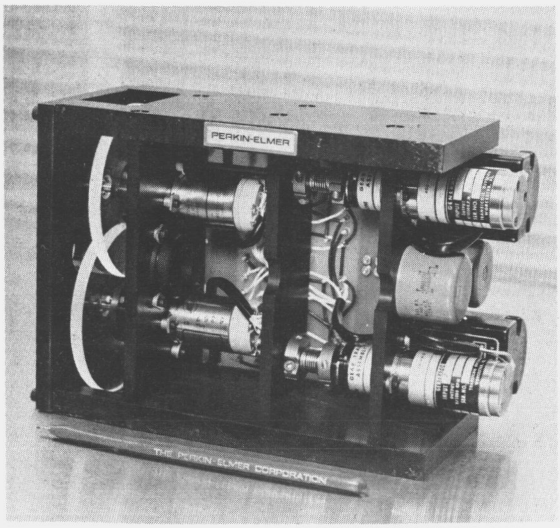


Figure 9.

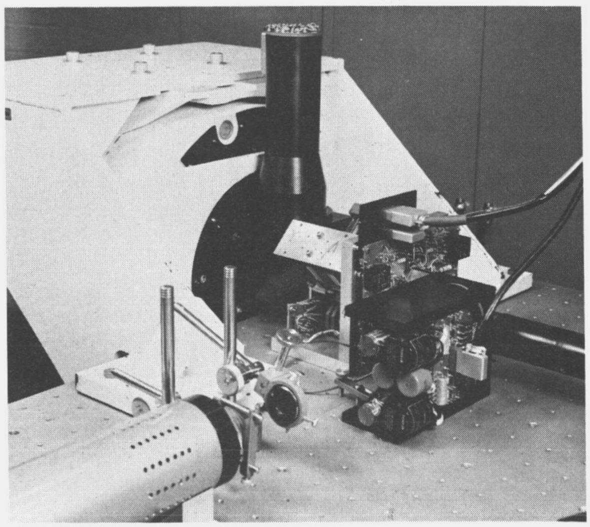


Figure 10.

The importance of each of these advances to the ultimate development of operational deep-space laser communications system is significant because four of the ten advances have been "reduce to practice" techniques (which are necessary for a laser communicator). Six of the ten advances improve the efficiency of the communication link itself by new and improved components. For example, the quantum efficiency of detectors has improved from 5 percent to 25 percent through the use of new dormer photomultipliers (which depend upon the principles of additional reflection). The shorter wavelengths, that is, going from 6328Å to 5300Å also assists in bringing up the quantum efficiency of the detectors. This is identical in effect, to improving the power output of the laser aboard a spacecraft in the communication link. Further, the new 5300Å lasers have power efficiencies in the vicinity of 1 percent as compared to the efficiency of helium-neon lasers with 0.1 percent. These same green lasers (5300Å) also have the capacity for higher outputs: values as high as 20 watts are technically feasible as compared to 0.2 watts of the helium-neon lasers. The new Fabry-Perot filters have transmissions in the range of 50 percent as compared with the Lyot filters with transmission efficiencies of 0.15 percent.

Without pursuing in depth the details of communication link signal/noise calculations, it can be seen that the factor of 5 improvement in quantum efficiency, the factor of 100 potential increase in power output, the factor of 3 increase in transmission efficiency of the predetection filter; if, all multiplied together, provide potential improvement factors of over 1000 (30 db).

The net result of these improvement factors is to reduce the telescope diameter and the weight of the laser communicator by appreciable factors and to introduce conservative safety margins. Thus, the Laser Communication System Experiment unit which was evaluated in 1966 as a half scale prototype for a deep space communicator (See Figure 8) is now adequate in size to function as a full scale communicator by substitution of lasers (i.e., 5300Å instead of 6328Å).

The rapid progress of the last three years in the laser art and science will continue, hopefully, and the experiments described in this report will be applicable to the future laser systems. As the laser communication efficiencies increase, there will be an ever increasing desire to apply these techniques to projects which could take advantage of them. However, the missing link in the application of laser communication techniques to interplanetary probes will be the propagation data on the laser beam for the two cases of up-going beams and down-going beams.

The last five illustrations, with the attendant supporting data, present convincing arguments that the state of the art of a deep-space laser communication system has graduated from an experimental level to a practicable level.

- <u>Pointing Technology Area</u> - The OTES mission plan as presently contemplated, provides the most complete space experiments set needed to develop the 1/100 arc second pointing technology for future NASA missions.

The large orbiting telescope systems which are being considered for future NASA missions are absolutely dependent upon precise pointing as well as diffraction limited optical systems. The modulation transfer function of the entire optical system - a precise measure of performance - degrades extremely rapidly if the motion of the image begins to approach the dimensions of the resolution element. In practical terms, the pointing system performance of a space telescope in angular measure - fractions of an arc second - must be significantly less than the resolution capability of the same telescope. Thus, Stratoscope II which is a 36 inch aperture diffraction-limited telescope has an angular resolution of 1/6 arc seconds (visible wavelengths) and yet the pointing system had to be 1/60 arc second. For the case where the telescope is being used to propagate a laser beam, communicator applications, these conditions are not as severe. For that type of operation, pointing system performance approximately equal to the beam divergence is adequate. Thus, the LCSE with its 0.4 arc second beam requires a pointing system in the vicinity of 0.1 arc seconds.

Because of the interest in 3-meter space telescopes for future NASA missions, the pointing precision experiments of the OTES (Experiment No. 9) are planned for 1/100 arc second down to 1/200 arc second. This latter number corresponds to 1/10 the diffraction limit angle of the 3-meter instrument.

The work completed in the Phase A Study by Perkin-Elmer in the evolution of pointing group of experiments (Experiment No. 9) points out the feasibility of conducting appropriate flight experiments to evaluate each of the four candidate techniques:

- Transfer Lens Experiments
- Flexure Gimbal Body Point Experiments
- Free Float Body Point Experiments
- Image Plane Equipment Motion Compensation Experiments

in each of the two orbited modes of operation.

- Connected to the cluster (with its man and large air drag induced disturbances)
- Autonomous (without man and with correspondingly lower amounts of orbital disturbances due to man, earth anomalies, magnetic field and air drag)

in each of the two background light conditions.

- Daylight
- Night.

The recommended plan is to orbit the 2-meter OTES at a < 500 mile altitude and compare this data with the LCSE data obtained at 20000 mile altitude.

Each of these pointing experiment combinations can be obtained to yield most valuable data by the presently configured OTES. Each of the instrument modules shown behind the telescope has its own autonomous guidance requirements and equipment. The concept details of the devices are included in this report in Chapter 3.

> Manned Astronomy Area - Due to the long trouble free life requirement and due to the need to provide equipment flexibility in the instrument section of a large space telescope, it is an inescapable conclusion that the future large optical space observatories will be maintainable by an astronaut in space. There are three OTES experiments directed at the utilization of man in the tending of future large orbital telescopes.

Experiment No. 3, the astronaut utilization experiment, is basically designed to learn how to support the large orbiting telescope system by having the astronaut perform two monumental task series:

1. Removing and replacing one of the mirror segments in the segmented optics group of the primary mirror.

2. Removing and replacing the scientific and engineering equipment modules located behind the primary mirror.

In the first series, the experiment would be conducted after the conduct of Experiment No. 1, the Primary Mirror Group. Based on data obtained from that experiment, it could be established which of the primary mirror segments has the poorest figure in the space environment, and that specific mirror segment would be replaced by a spare mirror segment which was carried aloft at the time of launch. The removal and replacement of one of the equipment modules behind the primary mirror is more complex than the initial mirror removal experiment because these units have electrical interfaces with the spacecraft and telescope as well as the close tolerances between optical and mechanical equipment.

Experiment No. 4, Scatterplate Photographs of the Primary Mirror, is too complex an operation to execute without the assistance of a specially trained astronaut. The performance of this task in the optical laboratory requires a high degree of optical know-how and dexterity. There is considerable question as to the likelihood of success of this experiment in the initial attempt. However, an important factor working for the success of this experiment is that the location at which the astronaut will conduct the experiment is at the very front of the telescope. This area is clear and unencumbered with other equipment.

Experiment No. 6, Mirror Coating in Space, requires the services of the astronaut to assist in the experiment. The mirror that is removed from the primary in Experiment No. 3 can be transferred to the mirror recoating tank by the astronaut. The astronaut would get it properly placed in the equipment, and after the recoating operations are completed, the mirror could be returned to the main telescope.

It is important that the reader recognize that for a space telescope to be serviced in flight, the instrument must be designed with this intent from the very beginning. Thus, the present state of the OTES conceptual design is such that the primary mirror, secondary mirror, figure sensor, scientific instruments and all functioning mechanisms are arranged so that access is provided to the astronaut from outside the telescope. Also, all mechanisms and functional units are modularized so that they may be replaced with the minimum of astronaut participation in EVA.

> Effects of Aerospace Environment Area - Both Perkin-Elmer and Lockheed have studied the launch environment of the Saturn IB and V systems and the effect it would have on the optical system. From this study evolved the need to provide an extendible telescope structure in order to accommodate either 2- or 3-meter aperture telescopes. The maintainability of large-aperture space telescopes of the future will be enhanced by the experiments which involve the space skills of the astronauts. The release of exhaust products from the astronaut life support systems and from the optical laboratory life cells has been analyzed as well as the light-scattering effects on space telescopes, from the molecular gas, aerosols, and particle debris.

During the OTES Phase A Program, there have been 15 optical technology milestones:

OPTICAL TECHNOLOGY MILESTONES OF PHASE A

Space Optics

1. Super cold telescope concept (-80°C temperature achieved passively)

   ± 4.5°C gradient tolerance predicted for -80°C

   < 1°C gradient for 3-meter mirror anticipated at -80°C

2. Diffraction pattern for 3-meter segmented optics computed and verified experimentally.

3. Active segmented optics demonstrated

Precise Pointing

4. 1/10 arc second laser tracking demonstration (Figure 11)

5. Body point plus all reflective transfer lens concept developed

6. Free float technique demonstrated (Figure 12)

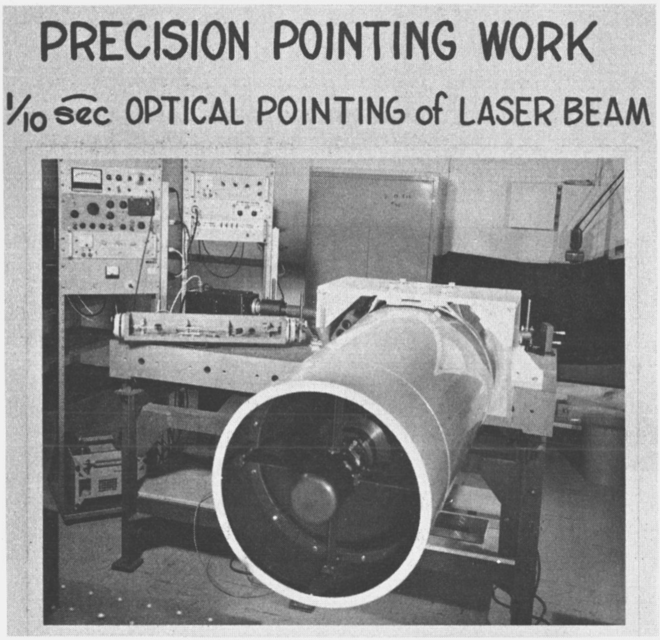


Figure 11. Laser Beam Pointing

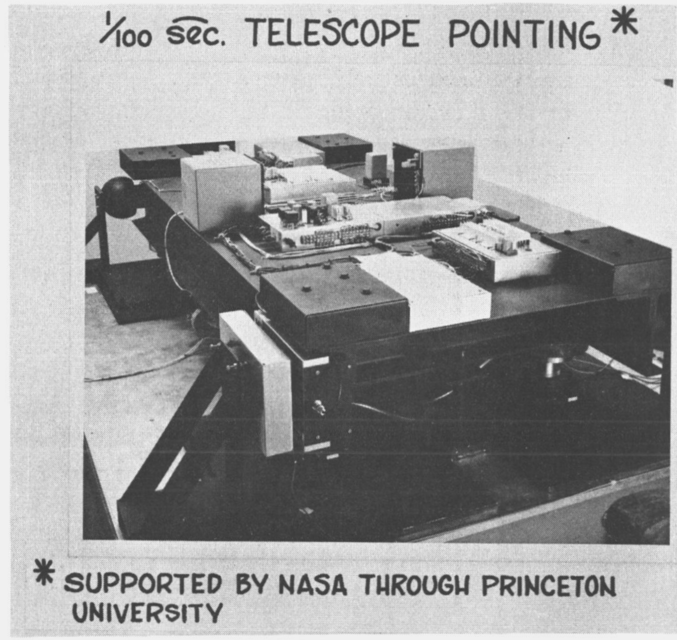


Figure 12. Free Float Pointing

Laser Communications

7. 10^{11} beam isolation measured

8. Laser beam wander (intensity fluctuation measured) <1%

9. 10^6 bits/second @ 10^8 miles computations completed for candidate lasers:

	5300Å	6328Å	10.6 micron coherent
Laser power output (watts)	3	0.140	20
Mirror diameter (meters)	0.5	1	1.5
Margin	3.6	1	1

10. Up-going beam spread @ 4880Å computed to be < 0.5 arc-seconds

Spacecraft

11. 22,767 n. mi. required orbit for communication experiments; 260 mile orbit most suited for optical experiments.

12. Thermal concept (coatings plus super insulation) evolved

13. Life Cell concept for the 3-meter telescope developed (MOTEL)

14. Compatibility with ATM Gimbals, Cluster and Apollo Flight Hardware established

15. 2-Meter telescoping tube concept developed as shown in Figure 13

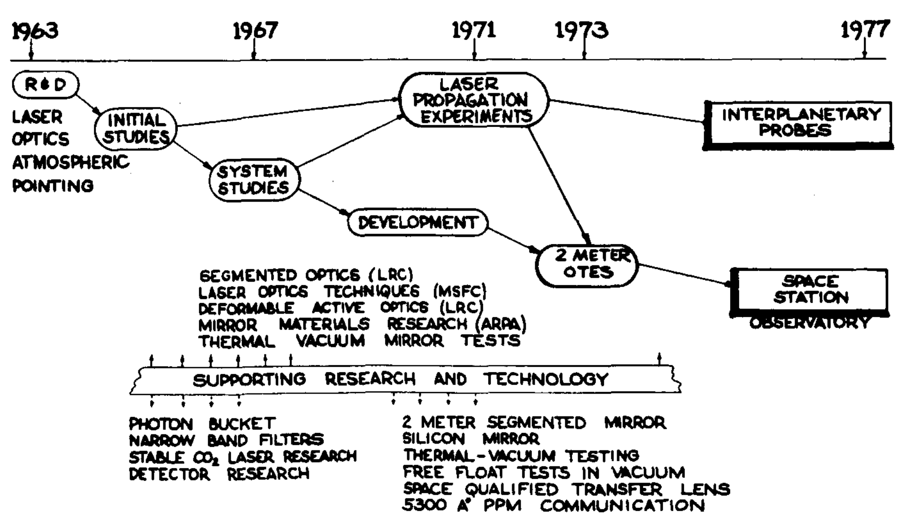
MISSION AREAS RECOMMENDATION

While Perkin-Elmer has studied the propsective relationship between short wavelength astronomy (i.e., gamma ray and X-ray) and the OTES Program, we have found that the instrumentation for this area is quite unique and bears little resemblance to the optical instrumentation needed for the OTES. In a similar manner, the broad general areas of planetology and meteorology are important in their own right, but have little in common with the impetus of the OTES. It is the Perkin-Elmer recommendation that the areas of optical technology in space which could benefit most from the conduct of space experiments utilizing Saturn launch vehicles are: large space optics, laser communications, astronaut experiments and atmospheric measurements.

SUPPORTING RESEARCH AND TECHNOLOGY RECOMMENDATIONS

The NASA Space Optics Technology Plan in Figure 1 shows the interrelations between the current OTES Study, the two flight experiment systems and the goals or missions. The supporting research and technology areas (SRT) that are presently funded are listed above the SRT bar while the Perkin-Elmer recommended new areas for SRT are shown below the bar:

NASA SPACE OPTICS TECHNOLOGY PLAN



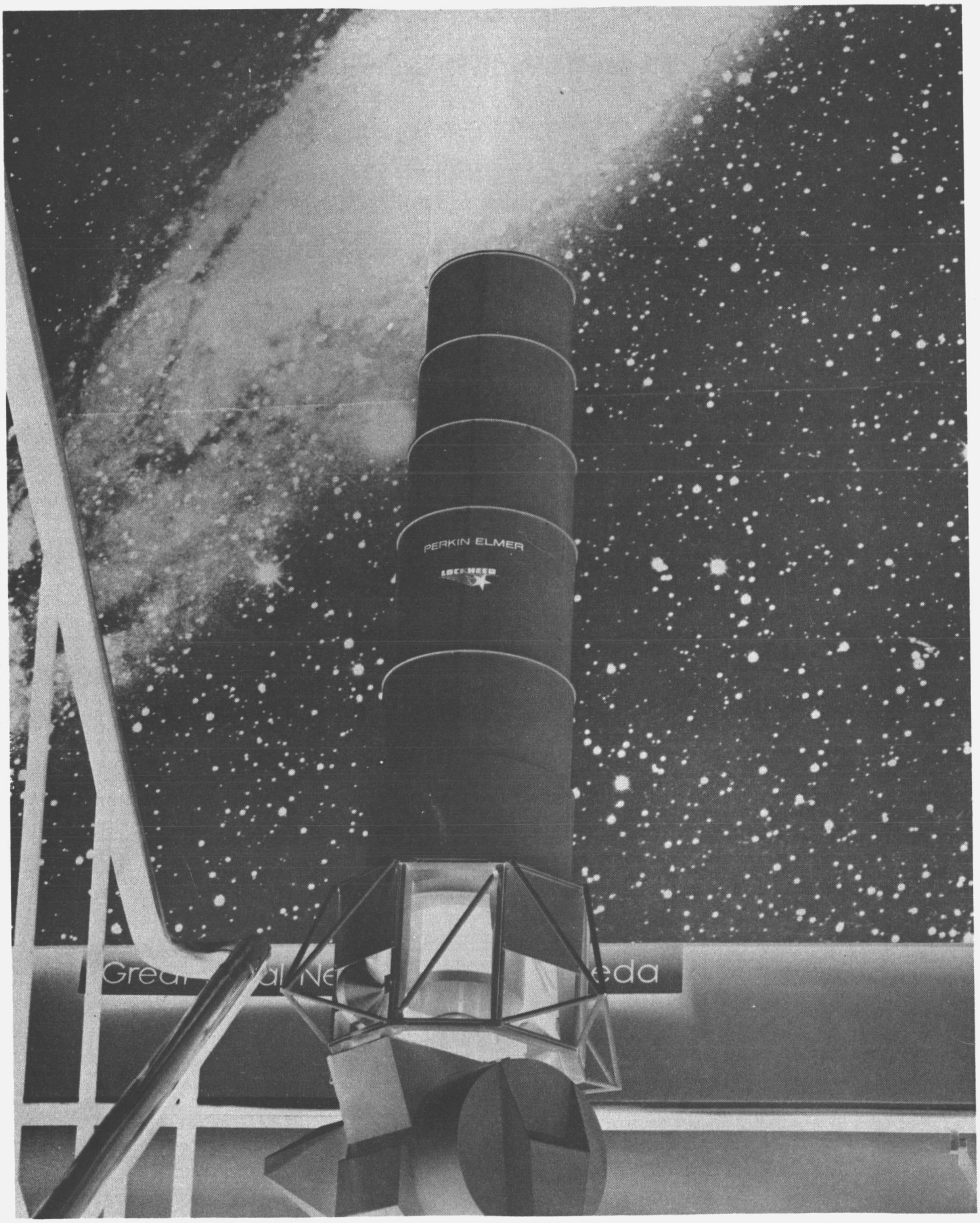


Figure 13. 1/10 Scale Model of the 2 Meter OTES